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Primary Productivity and Related Processes in New York Harbor as Reflective of Changing Water Quality

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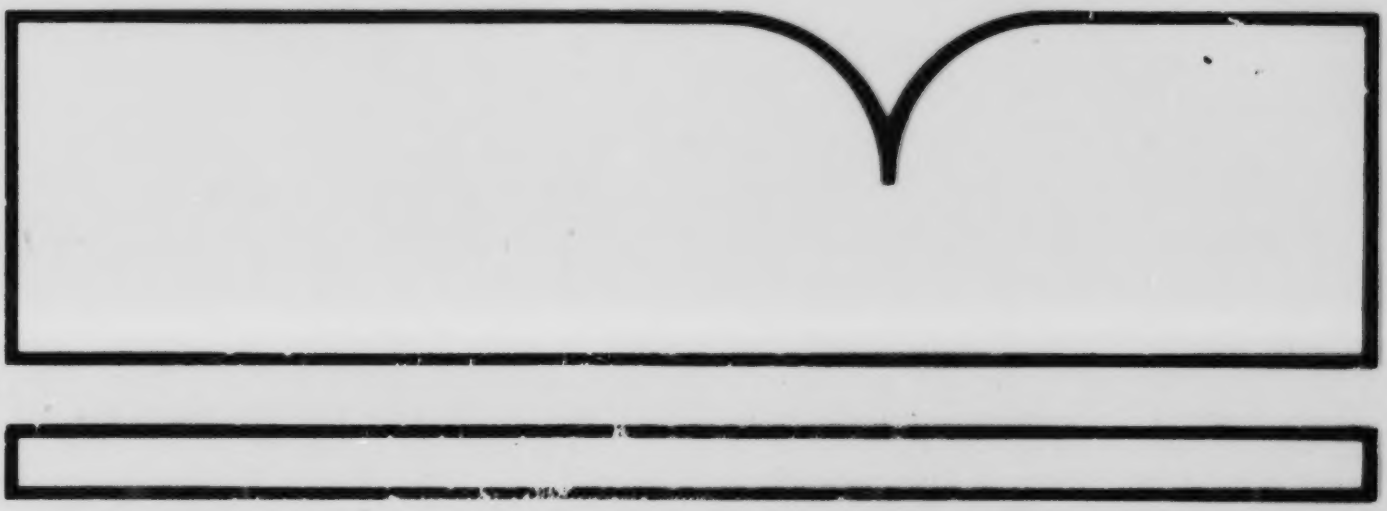

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PRIMARY PRODUCTIVITY AND RELATED PROCESSES IN NEW YORK HARBOR As Reflective of Changing Water Quality

by

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16. ABSTRACT

Relationships between photoplankton dynamics and changing water quality in New York Harbor were studied from 1974-1978. The study was to determine if removal of suspected toxic substances by advanced wastewater treatment, without simultaneous removal of excess dissolved nutrients (N and P) would result in nuisance phytoplankton blooms.

Observations suggest that stresses induced by poor water quality reduce potential productivity of diatoms in the estuary. In late spring-early summer these stresses may result from the inability of diatoms to utilize certain nutrients at ambient concentrations. In the fall, direct inhibition of diatom growth seems related to the presence of autoclave-degradable substances.

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PREFACE

All estuaries share certain common attributes. They represent zones of gradation between the sea and freshwaters, where the oceans and rivers combine to provide the necessary ingredients for the development of highly productive foodwebs, and where fisheries and spawning grounds flourish. Unfortunately, many estuaries share the common history of repository for wastes from surrounding population centers.

New York Harbor exemplifies a once-productive estuary which is now on the brink of ecological collapse. In the log of the Half Moon, Henry Hudson described how his ship's progress was impeded by the migration of shad down the river which bears his name. Today, the Hudson River fishery is reduced, and commercial fishing is banned because of PCBs in the biota. New York and Raritan Bays, once the source of oysters for European royalty have not produced a salable harvest in over a century. Human wastes and garbage are visible evidence of water quality degradation in New York Harbor.

Efforts are in progress to reverse the results of centuries of degradation, and to revitalize New York Harbor. However, to succeed it is first necessary to understand the present condition of the ecological system.

It has been our task these past four years to collect a baseline data set that will aid the management of water quality in the Harbor, and provide a reference point for progress. Too often well-intentioned changes induced upon an already unstable system result in unexpectedly deleterious and expensive consequences when made without understanding the system's ability to respond. Further, data-poor decisions that do not improve the "health" or quality of the system waste strained financial resources for pollution abatement.

In this study, we have attempted to provide the information and predictive capabilities needed to produce the most favorable management results in the shortest feasible time. We examined an entire range of parameters including light, turbidity and solids, temperature, salinity, pH, oxygen, nutrients, phytoplankton species and numbers, growth and production both in the field and under controlled laboratory conditions. We completed over 1400 collecting trips, including 36 cruises, and analyzed over 25,000 samples. We devoted considerable effort to defining what is "normal" for the estuary, and what is induced as a function of man's activities. We have attempted to differentiate between the long-term factors responsible for phytoplankton growth, production, succession, and inhibition, and the effects of pulsed inputs or occurrences of various substances on biological phenomena. At times, we found it necessary to modify existing analytical techniques and to develop new procedures, usable in New York Harbor and similar locations where heavy pollutant loads, boat traffic, and runoff from industrialization create a

unique set of environmental conditions. For example, we developed methods for conducting *in situ* incubation experiments in the turbulent and heavily navigated East River. We also developed laboratory assays to clarify some of the less obvious factors affecting water quality, such as vitamins, trace elements and toxins, which regulate phytoplankton growth and productivity.

Our work has established a foundation for further data collection, and from which sound management policies can be developed for New York Harbor. Perhaps more important, this effort can serve as a template for modeling studies of water quality in estuaries throughout the world.

ABSTRACT

Relationships between phytoplankton dynamics and changing water quality in New York Harbor were studied from 1974 - 1978. The study was devoted to determining whether removal of suspected toxic substances by advanced wastewater treatment, without simultaneous removal of excess dissolved nutrients (N and P) would result in nuisance phytoplankton blooms.

Phytoplankton community compositions were determined twice monthly at 5 alongshore stations around Manhattan Island and once to twice monthly at 6 stations in the mid Hudson River channel. Data on nutrients, physicochemical parameters, and production rates were also collected. Laboratory assessments of effects of water quality on the growth of Skeletonema costatum, (a common diatom in the estuary) were conducted from 1977 - 1978.

Diatom growth in the Harbor appears light-limited during winter-early spring, but the regression of productivity per unit biomass on light availability explains less of the variability in these parameters during late spring-summer (in winter $r^2 = 0.97$; in summer $r^2 = 0.59$). Furthermore, Harbor water collected between May and October inhibited growth of the diatom in batch culture experiments even when light and temperature conditions were optimal. In water collected during late spring-early summer the addition of silicate, and/or trace nutrients produced significant growth in cultures. Water collected between late summer and fall enhanced growth rates from 0 to 1.6 - 1.8 per day when the harbor water concentration in the medium was halved, or when the harbor water was autoclaved.

These observations suggest that stresses induced by poor water quality reduce potential productivity of diatoms in the estuary. In late spring-early summer these stresses may result from the inability of diatoms to utilize certain nutrients at ambient concentrations. In the fall, direct inhibition of diatom growth seems related to the presence of autoclave-degradable substance(s).

It is recommended that monitoring of phytoplankton populations and batch assay studies be incorporated into any strategy to improve water quality as an "early warning system" that proposed improvements are having undesirable effects. Further, it is suggested that no attempt be made to improve water quality in the estuary unless a total commitment of pollution abatement resources is feasible.

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This project resulted in the achievement of M.S. degrees in Biological Sciences by 11 Fordham University students and of Ph.D. degrees in Biological Sciences by M. P. Brown, R. J. Ingram, K. E. Belton, G. S. Kleppel, and W. B. Samuels of Fordham University.

SECTION 1

INTRODUCTION

Estuaries have long been identified as areas of great biological importance (Odum 1971). Compared with the productivity of the open ocean, estuarine and coastal waters represent about 10 percent of the total area of the world ocean and are responsible for about 50 percent of the primary and secondary production therein (Ryther 1959).

Because estuaries represent shelter from the sea, and often provide safe, natural harbors, they have played an important role as ports and centers of commerce in the history of the United States. The development of many estuaries as ports for large metropolitan areas has led to their use as receiving waters for domestic and industrial wastes. Waste discharge in estuaries has been related to increased rates of eutrophication and problems with toxic substances which accompany disposal practices.

Eutrophication is not necessarily deleterious, and some input of nutrients may actually enhance productivity. However, at some point, input of particulate and dissolved materials will no longer enhance production and may lead to deterioration of the system.

Toxicity can have several effects: one is to kill animals and plants. A second is to reduce fecundity, increase environmental stress, and reduce the stability of biological communities in a given area. A third, is to bioconcentrate in foodwebs creating a potential impact on human health. A fourth is to alter the types of organisms and foodwebs present without changing production or biomass levels.

A review of past studies (Suszkowski 1973) suggests that the New York Harbor - Lower Hudson River Estuary exemplifies an estuary degraded by domestic and industrial wastes. An historical summary of the progressive deterioration of the New York Harbor system is presented below.

With the realization that our nation's estuaries have fallen into a state of considerable deterioration, programs of restoration and resource management have been proposed. In developing strategies and programs for reclamation it has been necessary to ask questions regarding the feasibility and cost of restoration. To obtain realistic answers, it has been required that we study each estuary individually to determine a) its underlying dynamics, b) its present condition, and c) the potential for reclamation.

This report summarizes the results of four years' work and the analysis of over 25,000 biological and chemical samples for New York Harbor. Our work dealt specifically with the physico-chemical aspects of the harbor and with

the first level of biological production, the phytoplankton. An emphasis on primary production is important for several reasons. First, as primary producers, the phytoplankton are both a source of energy and a vehicle for pollutant transport to higher trophic levels. Second, as organisms which respond rapidly to environmental change, the phytoplankton serve as a barometer of environmental conditions and water quality. Third, as small particles, the phytoplankton serve as tracers of water movement. And finally, as a biological community, the phytoplankton represent a portion of the estuarine biota which should, under natural conditions, influence all other portions of the estuarine biota.

BACKGROUND

In this respect, New York Harbor is defined as Lower and Upper New York Bays, the East River, the Hudson River south of the George Washington Bridge, the Harlem River, Raritan and Jamaica Bays, Arthur Kill and Kill van Kull (Figure 1). New York Harbor is formed from the drowned Hudson and Raritan River Valleys (Jay and Bowman 1975), with tributaries draining some 42,000 km^2 (Suszkowski 1973).

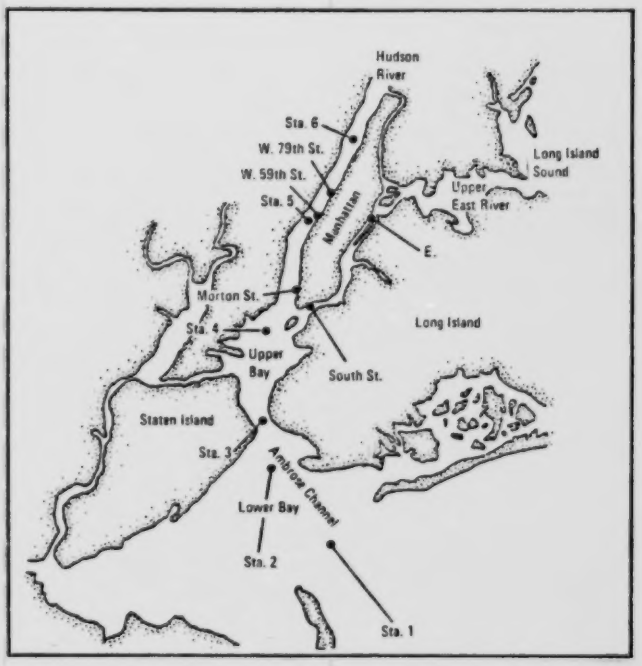

Figure 1. Locations of stations sampled in New York Harbor. Stations 1 - 6 were sampled once-twice monthly from 1976 - 1978. All other stations were sampled twice monthly from 1976 - 1978.

The Hudson River, with an average flow of 560 $m^3 \cdot s^{-1}$, is the principal freshwater source for New York Harbor (Giese and Barr 1967). Sewage effluents, small rivers and tributaries, and direct runoff from shore periodically contribute significant amounts of freshwater (Suszkowski 1973; ISC 1972a, b; Giese and Barr 1967; Dunn 1970; Weyl and Bowman 1972).

The waters of Lower and Upper New York Bays, and the East River are considered well mixed; those of the Hudson are partially mixed exhibiting weak seasonal stratification (Suszkowski 1973). Circulation patterns in the Harbor have been studied by Abood (1974) and Duedall et al. (1977) who reported a net nontidal seaward surface velocity of 10.0 - 17.5 $cm \cdot s^{-1}$, and a landward velocity along the bottom of 2.5 - 5.0 $cm \cdot s^{-1}$.

The loading of municipal sewage effluents to New York Harbor rose from 32 to 88 $m^3 \cdot s^{-1}$ between 1910 and 1971, increasing the estimated BOD from 4.1 x 10^5 $kg \cdot d^{-1}$ in 1905 to 6.5 x 10^5 $kg \cdot d^{-1}$ in 1971 (Suszkowski 1973). Raw and treated effluents were discharged from New York City at average rates of 18 (1971) and 51 - 72 $m^3 \cdot s^{-1}$ (1972) according to data reported by Suszkowski (1973) and the NYC Department of Water Resources (1972). The major sewage load occurs in the Hudson River (U.S. Department of Interior 1969); the East River contributes approximately 31% of the total (Pagenkopf and Bigham 1977). Transport of dissolved and particulate material from New York Harbor to western Long Island Sound, via the East River, has been considered largely responsible for the deterioration of water quality in the western part of the Sound (ISC 1972a). Bowman (1976) estimated that raw and treated sewage effluents enter the East River at a rate of about 35 $m^3 \cdot s^{-1}$, and that sources in the upper East River provide effluents to Long Island Sound at approximately 15 $m^3 \cdot s^{-1}$ (Hardy 1972). Storms result in the release of untreated sewage directly to the estuary, at an average flux of 283 $m^3 \cdot s^{-1}$ above the dry weather rate (Gross 1976 estimate).

Table 1 summarizes some of the data on N and P loading to New York area estuarine waters. In terms of primary algal nutrients, the Harbor received 90 - 169 metric tons of nitrogen, and 17 - 36 metric tons of phosphorus daily from 1971 - 1976 from sources associated with the estuary. Bowman (1976) calculated that western Long Island Sound receives 129, 5.2, and 11.0 tons of NH_3, NO_2, and NO_3 daily from New York Harbor.

New York City domestic wastes are comparable to the national average for nitrogen but contain only one-half of the phosphorus and one-eighth of the silica of the national average (Garside et al. 1976). The mean discharge of treated sewage wastes by all New York City pollution control plants was 51 $m^3 \cdot s^{-1}$ in 1972 (City of New York, Department of Water Resources 1972).

If the wastes from all the plants had a mean inorganic nitrogen concentration similar to that of the Tallman Island plant (1200 ug-at l^{-1}), the total discharge of nitrogen in treated wastes by New York City alone would be 73.1 metric tons per day (Garside et al. 1976).

In addition to the dry weather flow of municipal sewage effluent, New York Harbor receives, daily, an additional 20 $m^3 \cdot s^{-1}$ of untreated sewage (ISC 1972a; Suszkowski 1973). During storms, the combined storm and

sanitary sewer systems of New York City and other older sections of the metropolitan area release highly polluted sewage and stormwater runoff directly into the harbor without treatment (ISC 1972b). Gross (1976) estimated that, during storms, the average sewage overflow of the entire New York City region is approximately 394 $m^3 \cdot s^{-1}$ compared to the dry weather flow of 111 $m^3 \cdot s^{-1}$ (Gross 1976, estimate). Pagenkopf and Bigham (1977) estimate the average stormwater runoff into the Upper East River as 89 $m^3 \cdot s^{-1}$. It is apparent that, in New York Harbor, stormwater runoff can increase the volume of dry-weather municipal effluent three or four times. A large but unknown volume of industrial waste is also a major source of pollution. Thermal discharge to the Upper East River occurs at approximately 142 $m^3 \cdot s^{-1}$ from five power plants (Jones et al. 1975).

TABLE 1. ESTIMATED DAILY MASS EMISSIONS OF INORGANIC NITROGEN AND PHOSPHORUS TO NEW YORK METROPOLITAN AREA WATERS (METRIC TONS PER DAY)

Region	N	P	Reference
N.Y.-N.J. Metro	90	36	Ryther and Dunstan (1971)
Hudson River Estuary	169	17	Howells et al. (1970)
N.Y. City Effluents	73.1	-	N.Y.C. Dept. Water Res. (1972)
Hudson River/N.Y. Harbor	334	123	Mueller et al. (1976)
Hudson Estuary	160	-	Garside et al. (1976)
N.Y. Harbor	140	-	Quirk et al. (1973)
W. Long Island Sound	145	-	Bowman (1976)

New York Harbor waters are nutrient-saturated with respect to the phytoplankton biomass (Hardy and Weyl 1971). As much as 90 percent of the available inorganic nutrients are flushed into New York Bight coastal waters (Garside et al. 1976). Dunstan (1975) noted that under conditions of nutrient saturation, phytoplankton growth becomes more dependent upon the presence of trace substances. The roles of these substances in determining phytoplankton dynamics, both alone and in conjunction with the inhibitors present in the Harbor, have not been well studied.

NEED FOR PROJECT

In the coastal waters of New York State there is a particularly alarm-

ing situation that does not seem to be generally recognized. Due to the relative shortage of nitrogen compared to other nutrient elements required by algae in coastal waters (see e.g. Ryther and Dunstan 1971), discharge of nitrogenous matter from sources in New York, New Jersey and Connecticut into New York Harbor, Raritan Bay, Jamaica Bay and western Long Island Sound may cause mass algal blooms in these areas. However, in receiving areas that contain the highest concentrations of free algal nutrients, such as New York Harbor and the East River, algae are not a problem. This effect has been ascribed to light limitation (Malone 1977) but may also be due to the presence of one or several inhibitory factors. Once this factor is eliminated, degraded, or diluted out at the periphery of the Harbor, algal blooms occur. For example, phytoplankton blooms or "red tides" have occurred annually for at least 12 years in New York Harbor and in the New Jersey north shore area (Mahoney and McLaughlin 1977). McCarthy (1965), in his study of the ecology of phytoplankton blooms in Raritan Bay, found two periods of bloom conditions: one in the spring and the other in the summer, separated by a period devoid of phytoplankton. The spring diatom bloom was dominated by a single species, Skeletonema costatum, and the summer phytoplankton bloom was dominated by a chlorophycean, Nannochloris atomus (= Didymocystis). Mahoney (1974) studied phytoflagellate blooms occurring during the warmer months primarily outside Raritan Bay, and especially in Sandy Hook Bay, Lower Bay, and in New Jersey coastal waters. Some of these were apparently benign but others adversely affected biological and recreational resources. Of the several factors retarding algal growth, turbidity and toxic waste materials are known to be present in the Harbor. These factors are also the targets of conventional sewage treatment and discharge regulations. Thus, removal of these constituents by gradually advanced sewage treatment and control of toxic discharges could result, not in improved quality but in algal soup. Water quality might improve if the excess nitrogen were simultaneously removed along with other factors supporting algal blooms. However, considering that 90 percent more N is present than can be incorporated by the phytoplankton biomass under existing conditions, removal of the excess nitrogen seems unreasonable.

Elevated concentrations of urea, ammonia and nitrate are present in the East River and other areas of New York Harbor; this suggests that an incomplete functioning of the biochemical processes controlling the nitrogen cycle may be occurring in the estuary. This could be the result of some of the inhibitory factors or other conditions known to affect specific microorganisms and reactions. Removal of an inhibitor of nitrification by sewage treatment or effluent control would increase nitrification rates with associated utilization of dissolved oxygen and therefore would cause deterioration of water quality with respect to dissolved oxygen.

For the process to be economical, microbial activity, nitrification and denitrification should proceed at the highest possible rates in sewage treatment. This requires the absence of substances that could interfere with these processes. Also, microbial processes in the receiving waters should be used to greatest advantage, and sewage treatment or effluent control processes should maximize any benefit that naturally occurring processes might be able to provide.

The need for nitrogen removal may also alter priorities within the con-

cept of advanced treatment. Biochemical oxygen demand caused by algae grown on the nutrients from a given type of sewage is known to exceed the biochemical oxygen demand of that sewage. Hence, with certain limitations, nutrient removal could take priority over high grade BOD removal, and the requirements for nitrogen removal may affect the selection of treatment types in general.

Sewage treatment and discharge control efforts in the New York metropolitan area are massive. More progress is essential because not only are the Boroughs of Manhattan and Queens without recreational waters, but the problem areas affected by nuisance growths of algae now extend 20 miles from the center of the city. This creates considerable stress on the heavily populated suburban recreational resources and increasing expenditures of time and money for the urban population seeking recreational use of coastal waters.

The magnitude of the problem, the urgent need for continued progress, the current lack of construction capital, in addition to the excessive cost of land for sewage treatment facilities mandate the need to analyze the present situation intelligently before major decisions and large-scale investments are made.

It has been our purpose to examine relationships between phytoplankton abundance, species composition, biomass, productivity and growth as they may reflect changes in water quality in New York Harbor. We have attempted to provide basic information and analysis to provide insight into the highly complex multi-faceted phenomenon of phytoplankton bloom as influenced by physical and chemical variables. Time series data on several environmental parameters complementary to work conducted by others in recent years were collected. An attempt has been made to identify and understand the significant growth-controlling factors of various types of phytoplankton in the system, thus facilitating predictions of potential problems resulting from improved sewage treatment.

SECTION 2

CONCLUSIONS

A study was conducted relating phytoplankton biomass, species composition, productivity and growth to water quality in New York Harbor between 1974 and 1978. The study involved both regular sampling in the harbor and intensive laboratory work. Resulting from these efforts was the development of two potential water quality monitoring methods. The first requires regular sampling of phytoplankton at alongshore stations around Manhattan Island and examination for the presence and abundance of certain indicator species. The second involves use of growth and/or ^{14}C-uptake bioassays in which water quality is monitored using a common assay diatom.

An additional product of this study is a preliminary (soft) mathematical model which attempts in a primitive fashion to describe the fates of dissolved inorganic nutrients in New York Harbor as a function of hydrodynamic processes acting on the system. The model is designed for use during the period of low Hudson River flow.

Finally, based on an extensive sampling program we have gathered biological, chemical and physical data which agree well with those of Dr. T. C. Malone collected between 1973 and 1974. In combination with Malone's work, this effort provides expanded data-base and detailed information on physico-chemical and biological parameters for the mid-channel area between Lower New York Bay and the George Washington Bridge over a period including 1973, 1974, 1976 - 1978.

The following conclusions are based on the analysis of some 25,000 samples collected on 1400 alongshore sampling trips, 36 cruises and 3 years of laboratory studies.

1. In the estuary phytoplankton growth and productivity is light-limited during the winter and early spring. The importance of light as a limiting factor appears to decrease or operate in conjunction with other factors during the period from late spring to fall.

2. Diatoms, while present in the estuary throughout the year, fail to grow at expected rates even under conditions which should favor enhanced growth (increased light intensity and high nutrients).

3. It would appear that during late spring and early summer the growth of diatoms in New York Harbor is limited by insufficient concentrations of silicate and/or trace substances. This is not due to the absence of these materials from the system, but, we suspect, because stresses in the system (low light, toxic substances, etc.) reduce the ability of diatoms to incor-

porate certain nutrients at any but excessively high levels.

4. Diatom growth during late summer-fall seems to be inhibited by some dissolved substance(s), the effect of which is reduced by treatment with heat and pressure.

5. Our results concur with those of others (Malone in press) that have found that nutrient concentrations in the estuary are so extensive that only highly advanced wastewater treatment, accompanied by rerouting of storm and sanitation sewer systems, would significantly alter nutrient loads to Harbor receiving waters.

6. The magnitude of nutrients delivered to and removed from the estuary by phytoplankton appears minimal relative to the input from other sources and the dispersive character of the Hudson River. In periods of low flow, nutrients accumulate in the estuary.

7. Efforts to increase primary productivity during periods of high flow, to effect biological uptake and nutrient removal from the system, is probably not feasible within New York City, since the principal source of solids (which reduce light and hence limit productivity) is north of the city. Even if solids loading could be controlled, the effects in terms of nutrient removal would probably be minimal during the high flow season.

8. This study (four years +) as evidenced by intensive sampling and field analysis with concomitant laboratory experimentation and additional primitive modelling sets forth a broad data-base for subsequent studies of an in-depth character. Such additional in-depth studies before, during, and after development of treatment facilities when analyzed against our background situation should simplify our understanding of this complex ecological problem.

SECTION 3

RECOMMENDATIONS

There is consistent evidence that phytoplankton growth in New York Harbor is inhibited by toxic substances. The inhibitor(s) appear to be autoclave degradable substance(s).

We recommend that any improvement in New York City wastewater treatment system be undertaken with full awareness that the removal of potential toxicants from the estuary could possibly result in nuisance blooms. It seems impractical to us to go beyond the development of minimal treatment facilities unless in-depth studies are undertaken to discern the inherent reservoir load(s) of nutrients, inhibitors, and toxicants found in the Harbor which are constantly added to from the up-river water mass.

Consequently, attempts at solids control within the New York City sanitation system in order to increase the availability of light to the phytoplankton would produce negligible results, since most particulate material enters the Harbor and is generated north of the city. The lower Hudson is not a likely candidate for blooms because of turbidity levels alone. Therefore, any construction of municipal facilities in the metropolitan area must be coordinated in a regional effort to control upstream natural solids loading, and metropolitan sewage overflow. Along with intertidal velocities, these factors influence particle suspension regardless of nutrient toxicant removal in periods of low flow, as dry weather. We recommend the quantification of instream turbidity and light levels to provide a basis for estimating the instream limitations of phytoplankton blooms.

We believe that increases in primary productivity during the high flow period would result in only minimal removal of N and P. It is uncertain whether increased light penetration would significantly increase photosynthesis in the summer, but any increase at this time is likely to be translated into an accumulation of organic material in the estuary proper. Such an accumulation will result in algal-derived BOD. We recommend periodic monitoring of phytoplankton populations and batch-assay studies in order to evaluate trends in future phytoplankton kinetics. Therefore, if the wastewater treatment process is excessively upgraded, it must be done with extreme caution and with an accompanying monitoring effort.

SECTION 4

MATERIALS AND METHODS

ALONGSHORE SAMPLING

A program was initiated in 1974 to sample the phytoplankton of New York Harbor. The objectives were:

1) Identify seasonal changes in phytoplankton abundance and community composition.

2) Examine samples for potential nuisance species, including Olithodiscus luteus which blooms in Lower New York Bay (Mahoney and McLaughlin 1977), and Gonyaulax tamarensis, a toxic dinoflagellate, which has been expanding its range southward from the Canadian maritime provinces since 1968.

3) Generate a biological data set which could be expanded at minimal expense, and which would provide information useful in detecting changes in water quality.

To fulfill these objectives, 4 stations were established along the east and west shores of Manhattan Island. A fifth station (at West 57th Street) was added in 1976. This alongshore sampling program was considered appropriate for collecting a data set without costs for ship time which might limit continuation of the time series after the initial work was completed. The 5 alongshore stations are shown in Figure 1.

Water samples (1 liter) collected at surface, middle, and bottom depths were preserved with buffered formalin. Cells were concentrated (Kahlisco Plankton Centrifuge), identified and counted (Palmer and Maloney method 1954) by standard techniques.

STUDY EXPANSION

To generate a larger data set for use in mathematical simulation of estuarine dynamics, for comparison with alongshore data and for a broader understanding of present water quality in the estuary, the study was expanded to include the mid-Hudson River channel, Upper and Lower New York Bay stations shown in Figure 1 in July 1976. The 11-station survey area was sampled once each month until October 1977. The 5 alongshore stations were visited two weeks after each cruise, so that the twice-monthly sampling schedule was maintained. Between November 1977 and April 1978, the 11-station survey

was conducted twice each month.

The following parameters were measured at surface, middle, and near bottom depths at the alongshore stations, and at 0, 2.5 m, 5 m, 15 m (station 3 only) and near bottom at mid-Hudson channel stations:

Temperature, dissolved oxygen, salinity (YSI probes), light penetration (Secchi disc, and InterOcean photometer), dissolved inorganic nitrogen--nitrate, nitrite (cadmium reduction method, USEPA 1974), and ammonia (Orion Research 1975)-- total and ortho-phosphate (Strickland and Parsons 1972), suspended solids (APHA 1971), chlorophyll a (trichromatic method of Strickland and Parsons 1972), turbidity (Hach turbidimeter), and molybdate reactive silicate (Strickland and Parsons 1972).

The total sampling program resulted in the analysis of over 25,000 samples from 1400 alongshore samplings and 36 cruises.

IN SITU PRIMARY PRODUCTIVITY

From September 1977 to August 1978, primary productivity was measured at the alongshore station E. in the Lower East River located off East 80th Street. Measurements were made by filling 125 ml Erlenmeyer flasks with water collected from the surface and near bottom (generally 3 - 5 m). The near bottom sample was taken at approximately the 1% incident light penetration (1% I_0) depth. On several occasions, we measured light penetration in mid-channel of the Lower East River off East 80th Street and found that 3 - 5 meters was also the depth of 1% I_0 at this location.

Two light bottles and one dark bottle were inoculated with 2.5 uCi of $NaH^{14}CO_3$ and returned to depth for 8 hours. Samples were processed according to the recommendations of Strickland and Parsons (1972). Following incubation, samples were passed through pre-acid washed and rinsed 0.45 um Millipore filters at low vacuum, held over fuming HCl for 30 sec, then dissolved in Aquasol fluor (New England Nuclear). Samples were counted on a Packard Tricarb liquid scintillation counter and resulting data were corrected for background radiation, machine efficiency, and quenching by filters. Computation of primary productivity was performed as described by Strickland and Parsons (1972).

LABORATORY INVESTIGATIONS

General Strategy

New York Harbor receives materials ranging from simple inorganic nutrients, to complex synthetic hydrocarbons. The identities of all of the substances which could affect phytoplankton in the estuary are not known. Nor are the sources of the substances which are known always apparent.

Any experiment designed to elucidate the effects of these substances on the phytoplankton would of necessity require that New York Harbor water be

treated as a "whole medium." That is, attempts to examine the effects of individual or small groups of contaminants would be time consuming and costly, and would not account for interactive effects of all substances present.

Rather than make a priori judgements as to which contaminants were most important, we opted to consider water quality as a single entity. Certain treatments were performed on the water samples to obtain some notion of the nature of the types of substances which might have an effect on the phytoplankton.

Techniques

Three types of laboratory studies were conducted: 1) Monthly assays of the effect of East River water on the growth rate of a typical estuarine diatom, 2) Similar assays of ^{14}C-fixation rates, 3) Studies of the effects of metals on phytoplankton.

1) Growth rate studies: Each month between February 1977 and April 1978, water was collected from surface, middle and bottom depths at the South Street station along the East River. The water was mixed in a 10-liter carboy and divided into 3 subsamples. Each subsample was treated differently. One was passed through a sterile 0.2 um filter (CS), one was autoclaved (AUTO) (15 psi/15 min), and one was both filtered and autoclaved (F/A).

The treated water was used to prepare 10-ml batch cultures containing 1-ml of STP enriched seawater medium (Provasoli et al. 1957), and serially increasing concentrations of the treated Harbor water in saline solution.

Skeletonema costatum (Greville) Cleve, clone Skel, from axenic stock cultures (cf. Samuels 1979), was inoculated into the experimental media. Initial cell densities were approximately 10^3 cells$\cdot$ml^{-1}; stock cultures were in log phase when each experiment began. The cultures were incubated in Forma diurnal growth chambers at 20°C, illuminated for 14 h daily by GE-cool white, fluorescent bulbs (2500 uW$\cdot$cm^{-2}). Cell counts were made in a nannoplankton counting chamber (Palmer and Maloney 1954) at two day intervals for 14 days.

Additional work was conducted during periods when growth rates of the diatom were low. In these studies, the growth rates of S. costatum cultures prepared using additions of various trace nutrients and silicate were compared with growth in cultures to which no additions were made. Growth rate experiments were conducted in duplicate.

2) ^{14}C-fixation rates: Studies similar to those described above were conducted using ^{14}C-uptake as an indicator of the effect of East River water on the diatoms. S. costatum inoculated into 10-ml batch cultures of CS and AUTO water (F/A water was not used), was permitted to grow in the medium for 4 days. On day 5, cell densities were determined and 0.5 uCi of $NaH^{14}CO_3$ were added to each 10-ml culture. Incubation was extended for 2 h after which the cultures were filtered and processed for determination of ^{14}C uptake rate as described above.

3) Metals Experiments: In certain limited studies of New York waters, the occurrence of heavy metals and trace elements has been noted in concentrations which are toxic for certain algal forms previously studied (Howells et al. 1970). Notably Cu, Al, Mn, Pb, and Zn have been shown to exert distinct inhibitory effects on algal growth (Fish 1955; Goldman 1960; Lewin 1962). It is difficult from a search of the literature to place toxic limits or ranges for each trace metal. The possible synergistic effects of two or more metals acting together producing toxic effects interfering with growth, reproduction, and morphology of endemic microorganisms must be determined (Lewin 1962).

Another major concern in considering the potential toxicity of any trace metal is the ability of the algae to concentrate such elements above the levels found in the aquatic medium. Some algal populations have been found to concentrate many elements to the point of auto-intoxication. Such toxic accumulation has been noted for As, Ca, I, Mn, and in many cases for radioactive elements (Poli Karpov 1966).

The physiological availability of trace metals is influenced by chelators present in industrial wastes and by the high organic content of industrial and municipal wastes (Gurnham 1955). This adds another variable in the ranges and tolerances of algal species for these substances.

In November 1974, April and June 1975, cruises were made along three transects shown in Figure 2 to determine concentrations of heavy metals in New York Harbor and adjacent waters. Samples were analyzed by Dr. J. Alexander of New York Ocean Sciences Laboratory, Montauk.

Studies were also performed to examine the uptake and toxicity of four metals--cadmium (Cd), lead (Pb), nickel (Ni), and iron (Fe)--in three phytoplankton taxa.

Cultures of Platymonas subcordiformis, Dunaliella sp. and Nitzchia closterium were maintained in an incubation chamber at 20°C under 12 h light/day in DV medium, which is essentially DC medium (Provasoli et al. 1957), in which the organic nutrients have been deleted.

Experiments were performed in which cultures of these species prepared in triplicate were exposed to various concentrations of the above metals (introduced to the well chelated medium as salts) and uptake rates and inhibitory effects investigated (Stiffey 1981). Metal concentrations were determined using a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

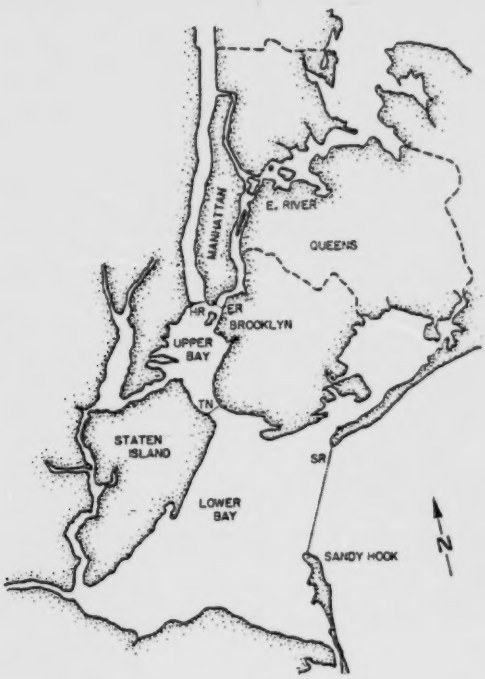

Figure 2. Transects of "heavy metals" cruises of November 1974, April and June 1975.

HR = Hudson River transect
ER = East River transect
TN = The Narrows transect
SR = Sandy Hook - Rockaway transect

SECTION 5

RESULTS AND DISCUSSION

PHYSICO-CHEMICAL PARAMETERS

Seasonal variability in salinity, temperature, dissolved oxygen and nutrient concentrations were measured in the estuary by Dr. T. C. Malone from 1973 - 1974. Our own measurements agreed well with these, and in conjunction with Malone's data, provide a time series of physical and chemical parameters in the lower Hudson River estuary. Since the physico-chemical dynamics of the estuary were explained by Malone (1977c) we present a summary of our findings. Our data for the mid-Hudson River channel and a model describing the dynamics of the system under certain conditions are provided as Appendices to this report. Details of the work are also found in Ingram (1979).

The rate of water column light attenuation, represented by the white light extinction coefficient is computed from the equation:

$$I_z = I_o e^{-kz}, \qquad (1)$$

where I_z and I_o = light intensities at depths z and o,

k = the light extinction coefficient (m^{-1}),

and, z = depth (m).

Mean extinction coefficients for high and low Hudson River flow periods (greater and less than 2.5×10^4 cfs, respectively) (data from USGS 1976 - 1978) are plotted over distance along the Hudson River mid-channel transect in Figure 3. The value of k at any station was highly variable, but, in general, the mean value of k decreased with distance seaward, and was greater during high flow than low flow periods. Inert suspended solids concentrations in the Harbor (Malone et al. in press), primarily from north of Manhattan Island, were the principal determinants of light attenuation rate.

Water temperatures varied from -1 to 25°C, lows occurring between January and February, and highs between July and September. As would be expected, seasonal temperature variability was greater in the Hudson River than in New York Bay. The Bay is apparently stabilized thermally by New York Bight Apex waters.

Hammond (1975) proposed that sewage contributes 4.86×10^{12} ug-at·d^{-1} of

dissolved inorganic nitrogen (DIN) to Upper New York Bay. The theoretical decay of this DIN as a function of Hudson River flow in a steady state mass balance on the volume of the Upper Bay is shown in Figure 4. The fit of our data to this scheme indicates that Hudson River flow is an important mechanism for transporting DIN out of the estuary.

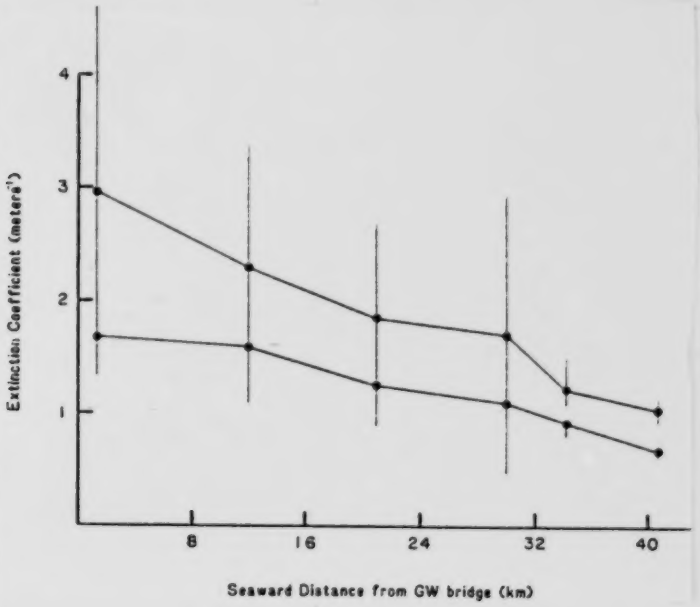

Figure 3. Mean extinction coefficients along the mid-Hudson channel as a function of distance from the George Washington Bridge.
Upper: high river flow period (2.5 x 10^4 cfs)
Lower: low river flow period (2.4 x 10^4 cfs)
Vertical bars are one standard deviation.

At most times during this study, ammonia constituted the bulk (generally 50 - 90%) of the total DIN. Nitrate delivered from upstream assumed a greater proportion of the total DIN during the spring high-flow period. However, only rarely did nitrate-N represent more than 50% of the total DIN.

Ammonia-N concentrations (25 - 88 ug-at·l^{-1}) were highest in the summer and were inversely related to freshwater flow ($r = -0.62$; $p < 0.01$). The isopleths shown in Figure 5 are representative of a trend suggesting an internal ammonia pool, possibly due to runoff or sewage discharge, in the Upper Bay (station 4). The ammonia is dispersed northward along the bottom, and southward along the surface.

Nitrite-N levels (0.3 - 40 ug-at·l^{-1}), along the mid-channel transect

exhibited a weak correlation with temperature, ($r = 0.56$; $p < 0.01$). The existence of a nitrite pool around station 6 suggests the conversion of ammonia to nitrite in that portion of the river.

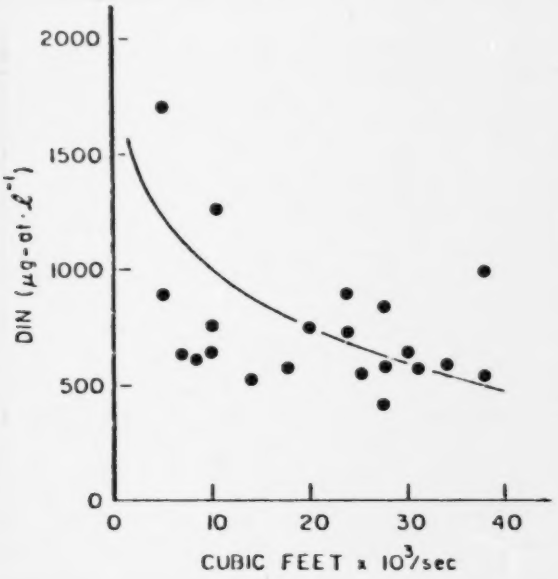

Figure 4. Relationship between dissolved inorganic nitrogen concentration and Hudson River flow.
Exponential decay of total DIN computed from data of Hammond (1975) for Upper New York Bay as a function of Hudson River flow rate (USGS 1976 - 1978), based on a mass balance. Circles represent DIN data generated at Station 4 (Upper New York Bay) during the present study.

McCarthy et al. (1975) and Liss (1976) proposed that nitrate in estuaries is derived from freshwater sources. Mid-channel transect NO_3-N concentrations (0.7 - 80.0 ug-at·l^{-1}) were correlated ($r = 0.87$; $p < 0.01$) with Hudson River flow rate measured at Green Island (USGS 1977 - 1978). Nitrate exhibited generally conservative behavior during high flow periods (Figure 6).

Total phosphorus levels varied from 0.6 - 17.1 ug-at·l^{-1}. About half of the total P was ortho-phosphate, the source of which appears to be sewage loading in the Upper Bay (Figure 7). A steady state mass balance of ortho-phosphate-P on the volume of the Upper Bay (Ingram 1979) demonstrates that while an exponential relationship between Hudson River flow and ortho-P concentration is apparent in the data collected over the study period, ortho-phosphorus generally behaves as a non-conservative substance over the year.

Silicate-Si delivery to the Harbor from the Hudson River followed the

hydrological cycle (Figure 8). The estimated input of a constant 20 metric tons of SiO_3-Si·d^{-1} from sewage is relatively insignificant during high flow periods, but amounts to approximately half of the summer silica load.

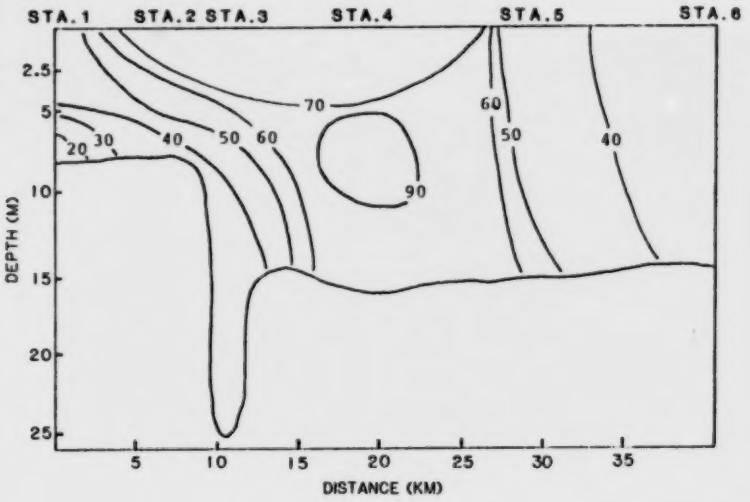

Figure 5. Ammonia-N (ug-at·l^{-1}) isopleths from the mid-Hudson channel on September 18, 1977.
The distribution of NH_3-N evidenced in this figure are representative of the low flow period.

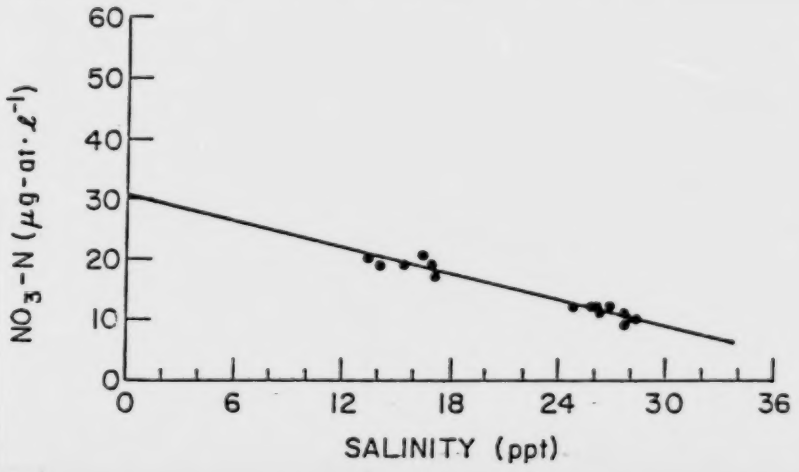

Figure 6. Relationship between nitrate-N and salinity in the mid-Hudson channel, February 6, 1977.
The relationship NO_3-N = 30 - 0.7 x salinity (r^2 = 0.76; $p < 0.01$) is representative of the conservative behavior of NO_3-N in the estuary.

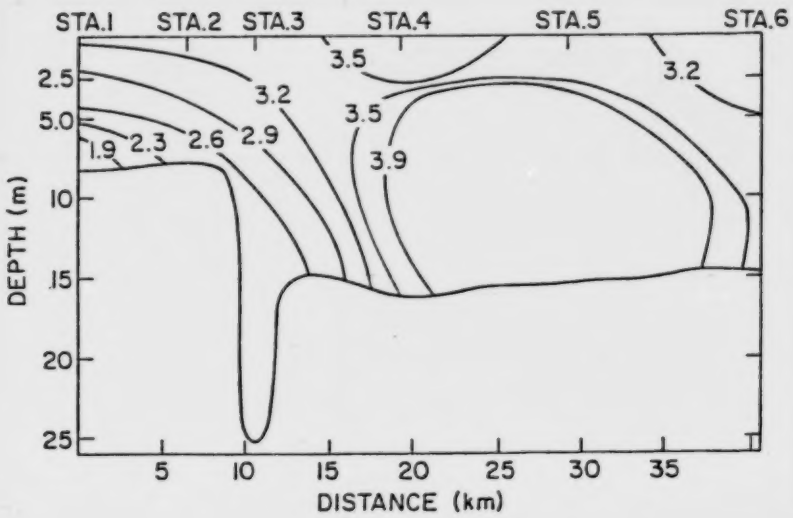

Figure 7. Isopleths for ortho-phosphate-P (ug-at·l^{-1}) in the mid-Hudson channel, September 28, 1977.
The isopleths are representative of ortho-P distributions during the low flow period.

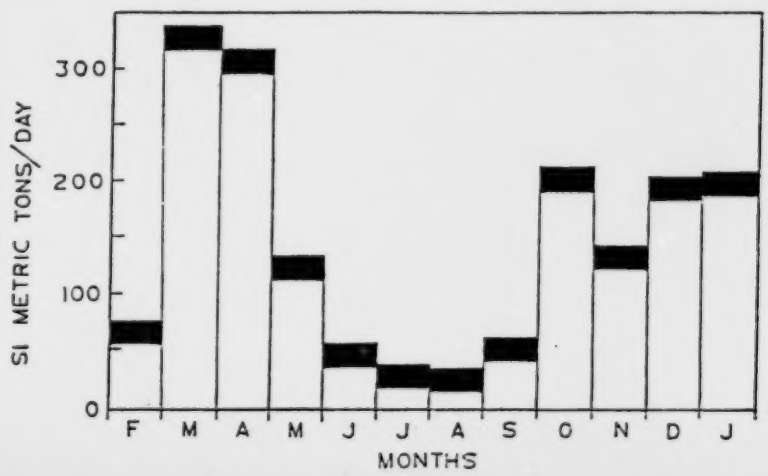

Figure 8. Average monthly rate of silicate-Si delivery to Upper New York Bay. Shaded area represents the estimated delivery of 20 metric tons of Si/day from wastewater discharge.

Metals concentrations determined by Dr. Alexander are presented in Tables 2 to 4.

Correlations between metals concentrations and other physical, chemical and biological parameters are presented in Tables 5 to 9. The correlation between particulate forms of Ni, Hg, Cu, Zn, Fe was high indicating that groups of metals are loaded together. These were also correlated with phosphorus concentrations, but did not show any significant relationships with phytoplankton biomass (chl a), suggesting that metals were primarily associated with particles other than the phytoplankton. Concentrations of dissolved Ni and Fe were negatively correlated with chl a in November 1974, but no relationship was apparent at other times.

PHYTOPLANKTON DYNAMICS IN NEW YORK HARBOR

Community Structure

The composition of the phytoplankton in the Hudson channel has been described previously (Malone 1977a). However, comparative information on alongshore distributions may be useful in future water quality management. Such comparisons were an integral part of this work. A list of the major phytoplankton taxa collected in New York Harbor between 1974 and 1978 is presented in Table 10. A detailed treatment of phytoplankton distribution in the Harbor was prepared by Belton (1979).

The planktonic flora in the estuary is decidedly marine. Most of the species collected were diatoms (approximately 45 species); Skeletonema costatum occurred most frequently. Thalassiosira pseudonana, Thalassiosira sp., Thalassionema nitzschoides and Asterionella japonica were also common. During all months at alongshore stations and in the summer months at mid-channel stations, the chlorophyte, Nannochloris atomus, was present in samples.

A succession from diatoms to chlorophytes and flagellates occurs in the estuary in late spring (Malone 1977a, 1977c; Mahoney and McLaughlin 1977). However, it is necessary to recognize that there is no time when diatoms are completely absent from the estuary.

In comparing frequency of species occurrence at alongshore stations with mid-channel (offshore) stations (Table 10) it is seen that frequencies of most species were higher at alongshore stations than in mid-channel, and there was less evidence of succession at nearshore stations. For instance, in mid-channel many of the diatoms disappeared during the summer; this was not the case nearshore. Hence, a fairly diverse diatom community is always present in the estuary, but in the summer it is confined to shoreline areas. Species which do exhibit consistent onshore-offshore distribution trends are Skeletonema costatum, Lithodesmium undulatum, Melosira nummuloides, Thalassiosira hyalina, T. nordeskoldii, Ceratium tripos (variable), Ebria tripartitan, Eutreptia marina, and Scenedesmus sp. These may be useful in future monitoring work conducted alongshore, as their occurrence seems somewhat representative of patterns in mid-channel.

TABLE 2. HEAVY METALS IN NEW YORK HARBOR - NOVEMBER 1974 (Units = ug/l)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
ER1-1S	2.4			2.2	2.4	3.4	15	30	<0.1	0.04	5.4	0.7	<4	3	38	12
-1M	0.4			2.9	3.0	4.7	41	200	2.5	0.10	10.9	0.9	<4	2	20	6
ER2-1S	<0.4			2.1	2.9	2.4	50	120	<0.1	0.01	13.4	0.4	<4	2	28	26
-1M	<0.4			2.6	1.3	2.8	39	180	<0.1	0.06	11.1	0.4	<4	3	27	21
-1B	<0.4			2.9	10.0	3.5	35	210	<0.1	0.03	8.8	0.3	<4	3	24	21
ER3-1S	4.5			2.4	5.0	3.4	20	170	<0.1	0.05	8.0	0.4		3	40	20
-1M	1.2	<0.1		2.6	1.6	3.2	9	190	0.4	0.05	7.1	0.4		2	24	11
-1B	<0.4	↓		3.3	11.7	5.1	33	270	<0.1	0.06	9.0	0.2		2	30	11
ER1-2S					2.9		50		<0.1	0.34	13.4				28	
-2M					1.3		39		<0.1		11.1				27	
-2B			↓	↓	10.0	↓	35		<0.1	0.21	8.8				24	
ER2-2S			ND	ND	31.	ND	33	↓	<0.2	0.18	11.6	↓		↓	49	
-2M			↑	↑	6.1	↑	29	ND	<0.1	0.27	9.4	ND		ND	22	ND
-2B	↓	ND			0.8		35	↑	<0.1	0.27	11.9	↑		↑	23	
ER3-2S	0.4				3.6		38		<0.1	>4	10.3		<4		37	
-2M					3.2		34		<0.2	>4	9.1				24	
-2B		↓		↓	12.1	↓	72	↓	<0.1	>4	9.8	↓		↓	23	↓
HR1-1S				2.6	8.6	3.4	24	210	<0.1	0.06	11.4	0.3		2	26	9
-1M		↓		2.2	1.4	2.4	36	160	<0.1	0.06	9.7	0.2		1	22	4
-1B	↓	<0.1		2.1	<0.4	2.4	38	150	<0.2	<0.01	7.9	0.2		1	22	5

(continued)

TABLE 2. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
HR2-1S	↓	↕		2.0	3.3	3.1	25	200	< 0.1	0.05	11.3	<0.1		3	38	9
-1M	4.6	<0.9		2.1	2.0	2.2	21	180	0.5	0.03	6.7	0.7		1	25	3
-1B	<0.4	<0.1		2.8	4.2	2.6	19	170	<0.1	0.08	9.2	0.3		<1	25	6
HR3-1S	|	<0.1		2.9	1.8	4.4	43	290	<0.1	0.05	10.8	0.5		<1	28	15
-1M	|	<0.1		6.0	<0.4	7.4	14	500	0.8	0.08	5.4	1.1		6	22	30
-1B	<0.4	0.3	↓	8.6	2.3	10.9	38	690	<0.1	0.19	10.3	1.6	↓	8	25	46
ER Pier 3 Bottom	<0.4	↓	↑	3.0	0.8	5.3	36	280	0.4	0.13	8.7	0.7	<4	2	51	36
TN1-1S	3.9	↓	|	↑	2.4	ND	25	↑	<0.1	1.80	6.2	↑	↓	↑	34	↑
-1M	3.8	↓	|	ND	2.4	↑	27	ND	<0.1	>2.00	5.7	ND	↓	ND	20	ND
-2B	3.2	↓	|	↓	3.2	↓	14	↓	<0.1	0.11	4.9	↓	↓	↓	36	↓
TN1-2S	5.4	<0.1	|	2.6	2.7	4.4	22	180	<0.2	0.09	8.8	0.4	↓	2	28	22
-2M	4.2	↓	|	3.2	2.8	4.2	27	260	<0.1	0.08	5.8	0.5	↓	3	25	25
-2B	3.7	↓	|	3.5	2.5	4.6	18	310	<0.1	0.06	5.7	0.5	4.2	3	24	21
TN1-3S	3.5	↓	|	↕	2.4	↓	22	↑	<0.1	0.08	7.5	↑	↑	↑	28	
-3M	3.4	↓	ND	ND	2.7	ND	24	ND	<0.1	0.16	6.3	ND	↓	ND	21	ND
-3B	4.4	↓	|	↕	2.2	↓	14	↓	0.0	0.03	5.0	↓	↓	↓	16	
TN1-4S	4.2	↓	|	2.0	3.5	2.7	63	140	<0.1	0.03	7.1	0.3	<4	1	33	6
-4M	3.9	↓	|	3.4	2.4	4.4	14	330	1.8	0.08	4.0	0.7	↓	3	15	23
-4B	1.3	0.1	|	4.4	1.6	6.0	12	360	<0.2	0.10	3.6	0.9	↓	5	27	62

(continued)

TABLE 2. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
A1 -1S	2.5	↑		0.4	2.4	1.2	9	40	<0.2	1.00	2.7	0.2	↓	<1	26	4
-1M	2.8	↑		0.2	1.8	0.2	17	40	0.6	1.10	2.4	0.2	↓	<1	8	2
-1B	3.7	0.1		0.2	1.9	0.2	18	40	2.1	0.66	2.6	0.1	10.6	<1	12	3
B1 -1S	0.8	↓	↓	0.4	1.8	0.8	8	50	<0.1	1.26	2.6	0.3	↑	<1	18	4
-1M	3.9	↓	↓	0.3	1.7	0.3	12	50	0.7	1.10	2.7	<0.1	<4	<1	10	2
-1B	4.3	↓	↓	0.5	2.5	0.5	21	80	0.3	1.16	5.8	<0.1	↓	<1	9	2
C1 -1S	5.5	↓	↓	0.3	2.4	3.7	18	60	0.5	1.41	4.8	<0.1	↓	<1	21	4
-1M	3.6	↓	↓	0.3	1.8	2.8	28	60	<0.1	0.70	3.2	<0.1	↓	<1	12	<1
-1B	4.0	↓	↓	1.0	1.9	1.9	13	180	<0.1	2.58	2.9	<0.1	↓	<1	16	3
D1 -1S	4.6	<0.1	↑	0.4	1.8	2.7	8	44	<0.1	0.18	4.2	<0.1	<4	<1	20	5
-1M	4.7	↑	↓	0.5	1.7	2.7	12	21	<0.1	0.49	3.9	<0.1	↑	<1	13	3
-1B	4.5	↓	↓	0.6	2.5	1.6	21	20	0.1	2.07	2.9	<0.1	↓	<1	10	5
E1 -1S	3.3	↓	ND	0.5	3.7	2.7	18	11	<0.2	1.42	4.4	<0.1	↓	<1	23	6
-1M	4.4	↓	↑	0.5	2.8	2.2	28	20	<0.2	0.07	4.4	<0.1	↓	<1	11	5
-1B	3.9	↓	↓	0.5	1.9	1.5	13	9	0.6	0.10	3.7	<0.1	↓	<1	11	3
AC1-1	4.3	↑	↓	↑	2.8	↑	14	↑	<0.1	↑	4.5	↑	↓	↑	27	↑
	3.1	ND	↓	ND	1.7	ND	9	ND	<0.1	ND	4.7	ND	↓	ND	11	ND
	4.3	↓	↓	↓	5.4	↓	14	↓	0.8	↓	3.7	↓	↓	↓	19	↓
	1.6	↓	↓	↓	1.8	↓	14	↓	0.6	↓	2.7	↓	↓	↓	23	↓

ND = Not Determined; Dis = Dissolved; Part = Particulate

TABLE 3. HEAVY METALS IN NEW YORK HARBOR - APRIL 1975 (Units = ug/l)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
ER1-1S	0.5	0.4		3.5	3.3	4.2	14	470	<0.2	0.06	2.9	0.7	<.9	<3	21	86
-1B	0.9	1.6		12.6	1.6	13.2	33	1090	<0.2	0.13	5.4	1.4	<.9	8	22	210
ER1-2S	0.7	<0.5		3.6	2.5	4.2	20	430	<0.2	0.03	3.0	0.5	<.9	< 5	9	31
-2B	0.3	<0.5		18.4	1.1	17.2	43	1560		0.18	3.6	2.9	<.9	12	9	83
ER1-3S	0.3	0.5		4.9	3.5	5.2	40	540	<0.2	0.06	4.9	0.8	<.9	4	14	47
-3B	0.7	<0.5		5.4	5.0	6.3	17	540	0.4	0.02	9.0	1.1	<.9	5	16	47
ER2-1S	0.2	<0.5		4.1	1.8	3.6	16	460	<0.2	0.04	2.8	0.5	<.9	< 5	11	55
-1B	<0.1	1.0		12.4	4.3	13.1	27	1170	<0.2	0.19	7.1	2.0	<.9	7	9	92
ER2-2S	0.1	<0.5		5.2	1.4	2.9	17	340	<0.2	0.03	3.2	<0.3	0.9	< 3	6	29
-2B	<0.1	<0.5		5.2	1.5	10.2	15	850	< 0.2	0.12	3.9	1.4	<.9	8	10	72
ER2-3S	0.2	<0.5		5.2	4.0	5.5	22	500	<0.2	0.06	7.7	0.9	0.9	4	17	38
-3B	0.2	<0.5		5.2	4.6	5.5	17	450	0.4	0.01	6.9	0.6	1.3	5	14	31
ER3-1S	0.2	0.7		4.2	1.5	4.4	15	480	<0.2	0.08	2.4	0.7	<.9	< 6	8	46
-1B	0.2	0.9		17.0	1.5	18.4	17	1600	0.4	0.31	2.6	2.3	<.9	12	10	85
ER3-2S	<0.1	<0.5		4.0	1.4	4.5	20	470	<0.2	0.08	2.9	0.7	<.9	< 5	9	43
-2B	1.3	<0.5		7.9	1.0	8.2	19	750	<0.2	0.07	4.2	1.0	<.9	6	6	37
ER3-3S	0.1	<0.5		5.3	1.7	6.0	8	480	0.3	0.09	2.2	1.1	<.9	4	3	42
-3B	0.2	<0.5		4.2	3.2	5.3	12	460	<0.2	0.06	5.8	1.0	<.9	4	11	37

(continued)

TABLE 3. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
HR1-1S	<.1	<0.5		2.9	1.4	3.4	14	400	<0.2	0.08	2.7	0.5	< .9	< 5	7	39
-1B	<.1	<0.5		9.9	0.6	10.1	12	930	<0.5	0.12	2.0	1.3	< .9	< 5	7	100
HR1-2S	0.2	<0.5		2.3	3.0	3.2	18	420	<0.2	0.06	2.7	0.5	0.9	< 5	11	32
-2B	1.0	<0.5		4.3	2.8	4.3	11	400	<0.2	0.06	4.5	0.6	< .9	< 5	8	36
HR1-3S	0.1	<0.5		2.3	10.7	2.1	55	510	<0.2	0.04	10.6	0.8	2.3	< 4	10	38
-3B	0.2	<0.5		8.1	1.4	7.6	18	880	0.3	0.14	3.3	1.4	1.4	< 5	7	46
HR2-1S	<.1	<0.5		2.6	1.5	2.4	12	360	<0.2	<0.01	5.4	<0.3	< .9	< 5	7	40
-1B	0.1	<0.5		10.7	1.3	10.4	28	940	<0.2	0.10	3.5	0.9	< .9	8	10	62
HR2-2S	<.1	<0.5		4.3	1.5	4.3	12	400	<0.2	0.06	2.7	0.6	< .9	< 5	12	77
-2B	0.9	<0.5		2.1	1.7	2.1	16	390	0.5	0.09	2.7	0.6	< .9	< 5	8	31
HR2-3S	<.1	<0.5		2.0	1.2	2.3	22	510		0.06	0.8	0.9	< .9	< 4	4	31
-3B	0.2	<0.5		8.4	1.9	8.8	19	1010	<0.2	0.13	8.6	2.8	< .9	< 5	12	41
HR3-1S	0.2	0.5		2.8	2.3	2.9	21	460	<0.2	0.05	3.0	0.5	0.9	< 5	13	39
-1B	0.4	<0.5		15.4	1.4	13.1	22	1440	<0.2	0.21	6.3	1.9	<.9	<10	13	112
HR3-2S	<.1	<0.5		2.2	2.3	2.2	16	390		0.04	4.0	0.7	< .9	< 5	9	42
-2B	0.8	<0.5		7.5	2.2	8.9	30	720	<0.2	0.09	4.9	1.5	< .9	5	16	48
HR3-3S	0.2	<0.5		2.4	3.6	2.4	31	540	0.3	0.04	7.0	1.1	2.6	< 5	13	38
-3B	0.2	<0.5		6.1	1.4	6.7	11	900	0.5	<0.01	3.2	1.5	< .9	< 5	16	73

(continued)

TABLE 3. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
TN1-1S	0.2	<0.3		3.2	3.3	3.2	15	300	<0.2	0.01	2.9	0.4	< .9	2	102(?)	57
-1B	0.4	<0.3		5.5	2.3	5.6	23	630	<0.2	0.09	2.4	0.7	1.2	4	10	37
TN1-2S	0.8	<0.3		2.0	1.0	2.0	9	240	<0.2	0.01	2.2	0.4	<.9	< 3	10	46
-2B	0.2	<0.3		2.2	2.3	2.2	8	250	<0.2	0.05	2.0	0.5	<.9	< 3	23	27
TN1-3S	<.1	<0.4		7.2	1.1	6.5	8	730	0.8	0.14	1.9	0.8	<.9	6	5	59
-3B	<.1	<0.4		11.6	0.8	11.2	8	1320	<0.2	0.10	2.2	1.6	<.9	7	6	67
TN1-4S	.1	<0.4		5.3	1.1	4.4	10	480	0.3	0.07	2.3	0.8	<.9	< 4	6	35
-4B	0.4	<0.4		8.1	2.1	8.3	8	780	<0.2	0.07	4.4	1.3	<.9	6	25	43
TN2-1S	0.9	<0.3		2.2	1.7	2.2	16	250	0.3	0.05	3.3	0.4	0.9	< 2	12	23
-1B	0.5	<0.3		5.9	1.4	6.1	6	680	0.2	0.09	3.3	1.2	0.9	4	6	45
TN2-2S	<.1	<0.3		2.1	1.0	1.8	9	240	0.4	0.01	2.7	0.5	<.9	<3	5	20
-2B	0.3	<0.3		3.2	2.0	2.6	14	310	<0.2	0.04	1.6	0.5	0.9	3	18	24
TN2-3S	<.1	<0.4		2.0	1.3	2.0	11	290	<0.2	0.03	3.8	0.4	<.9	<3	7	29
-3B	<.1	<0.4		4.6	0.9	4.8	8	600	0.9	0.05	1.9	0.8	<.9	4	6	32
TN2-4S	.1	<0.4		4.7	0.8	4.4	10	490	<0.2	0.06	2.3	0.7	1.2	<4	6	36
-4B	0.4	<0.4		11.2	1.5	10.8	10	1020	<0.2	<0.01	2.3	1.5	2.2	5	17	47
TN3-1S	0.8	<0.3		3.4	2.9	3.5	16	350	0.7	0.06	4.5	0.7	<.9	3	9	45
-1B	0.8	<0.3		8.4	2.6	7.6	13	890	1.8	0.13	2.2	1.3	<.9	6	6	46

(continued)

TABLE 3. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
TN3-2S	<.1	<0.3		2.8	0.9	1.6	5	240	0.6	0.05	4.2	0.5	<.9	< 3	2	20
-2B	0.6	<0.3		4.2	3.3	4.3	9	490	0.8	0.07	1.9	0.6	< .9	4	26	31
TN3-3S	1.1	<0.4		3.1	3.1	1.6	10	300	<0.2	0.04	4.3	<0.5	<.9	< 5	10	39
-3B	<.1	<0.4		11.1	1.4	9.3	6	1100	0.3	0.15	3.0	1.4	<.9	6	10	66
TN3-4S	<.1	<0.4		3.0	1.4	2.4	13	350	<0.2	<0.01	2.7	0.5	<.9	< 4	8	34
-4B	0.4	<0.4		8.6	1.3	9.2	7	820	<0.2	0.12	2.5	1.2	<.9	6	19	50
D -1S	0.3	<0.1		1.4	2.2	1.0	17	150	<0.2	0.02	2.2	0.2	<.9	< 2	1	12
-1B	<.1	<0.1		2.1	1.2	1.6	6	230	0.3	0.02	1.7	0.2	<.9	< 2	2	26
D -2S	<.1	<0.2		3.3	1.9	3.1	14	370	0.8	0.04	2.3	0.4	<.9	3	2	29
-2B	<.1	<0.3		3.8	2.3	4.0	13	480	0.3	0.08	2.0	0.6	<.9	4	5	100
D -3S	<.1	<0.2		2.5	2.1	2.3	11	300	0.3	0.06	1.6	0.4	<.9	< 2	2	34
-3B	0.6	<0.2		3.5	2.6	3.6	10	420	0.3	0.06	2.1	0.7	<.9	< 2	9	36
E -1S	Lost	<0.2		2.0	Lost	1.8	Lost	240	<0.2	0.02	Lost	0.2	Lost	2	Lost	25
-1B	<.1	<0.2		2.6	2.0	2.6	8	320	<0.2	0.05	2.8	0.6	<.9	3	4	16
E -2S	<.1	<0.3		2.6	1.7	2.7	12	350	<0.2	0.04	1.9	0.6	<.9	< 3	3	32
-2B	0.1	0.9		4.2	1.3	4.8	10	560	<0.2	0.06	3.1	0.7	<.9	4	11	32
E -3S	<.1	<0.2		2.4	2.2	2.0	9	260	<0.2		2.8	0.4	< .9	< 2	4	30
-3B	1.9	<0.4		5.6	2.8	5.4	25	680	<0.2	0.12	3.2	1.0	1.7	< 4	1	52

ND = Not Determined; Dis = Dissolved; Part = Particulate

TABLE 4. HEAVY METALS IN NEW YORK HARBOR - JUNE 1975 (Units = ug/l)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
ER2-1S				1.7	6.8	2.4	11	180	1.4	.03	6.0		1.2		64	19
-1B				1.9	4.7	2.1	11	160	2.1	<.01	6.6		1.4		41	11
HR2-1S				2.1	5.0	2.0	10	220	<0.8	<.01	5.4		1.9		55	14
-1B				2.6	2.3	1.4	16	120	1.3	.04	4.1		<0.9		35	6
TN2-1S				2.0	4.2	1.8	11	140	1.6	.02	4.7		<0.9		35	15
-1B	<0.1	<0.2	ND	2.1	3.2	1.8	9	200	4.0	.02	3.0	<1.0	<0.9	<3	23	22
A -1S				0.3	3.2	0.8	7	52	2.4	.01	2.2		<0.9		23	10
-1B				0.6	5.1	1.0	8	67	2.9	<.01	3.2		<0.9		25	6
C -1S				0.5	4.7	1.2	8	67	1.0	.02	5.3		<0.9		46	21
-1B				0.5	3.4	0.9	9	54	0.8	.02	4.2		1.1		23	7
E -1S				0.3	4.4	1.3	10	61	1.3	<.01	5.7		<0.9		42	16
-1B				0.5	1.1	0.6	5	60	1.9	<.01	2.0		<0.9		16	6
A -1S	<0.1	<0.1		0.3	2.2	0.5	8	60	<0.2	0.01	1.1	0.2	<.9	<2	6	9
-1B	<0.8	<0.1		1.6	2.8	2.0	10	210	0.3	0.01	1.0	0.5	<.9	2	5	14
A -2S	<.1	<0.1		0.4	1.3	0.4	5	70	6.2(?)	0.02	0.6	0.2	<.9	<2	<2	28
-2B	<.1	<0.1		0.5	2.2	0.5	7	70	<0.2	0.02	1.0	<0.1	<.9	<2	2	7
A -3S	0.1	<0.2		0.8	1.5	0.9	11	130	<0.2	0.05	2.2	0.2	<.9	<2	2	14
-3B	Lost	<0.2		0.5	Lost	0.4	Lost	70	0.2	0.01	Lost	0.2	Lost	<2	Lost	11
B -1S	<.1	<0.1		0.9	1.2	0.7	9	110	<0.2	0.02	0.9	0.1	<.9	<2	2	10
-1B	0.6	<0.1		1.2	2.2	1.4	6	140	<0.2	0.02	9.5	0.1	<.9	<2	4	13
B -2S	0.1	<0.1		1.4	1.8	1.0	7	150	<0.2	0.01	2.4	0.2	<.9	<2	5	12
-2B	0.8	<0.1		0.9	1.8	0.9	12	120	0.3	0.02	1.0	0.2	<.9	<2	4	15

(continued)

TABLE 4. (continued)

Station	Cd		Cr		Cu		Fe		Hg		Ni		Pb		Zn	
	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part	Dis	Part
B -3S	<.1	<0.2		1.8	1.2	1.4	15	200	<0.2	0.02	1.9	0.3	.9	2	1	29
-3B	<.1	<0.2		1.0	<0.1	1.4	< 2	180	0.7	0.03	<2	0.2	.9	2	2	14
C -1S	0.2	<0.1		0.9	2.2	0.8	12	120	0.5	0.01	1.7	0.2	.9	2	4	19
-1B	0.3	<0.1		1.6	1.5	1.6	11	190	<0.2	0.03	1.0	0.2	1.3	2	3	10
C -2S	<.1	<0.1		2.1	2.9	2.3	10	230	<0.2	0.04	3.1	0.3	1.5	2	7	17
-2B	1.2	<0.1		2.2	2.8	2.0	8	240	0.3	0.02	2.0	0.4	.9	2	4	18
C -3S	<.1	<0.2		1.9	0.4	1.8	< 2	220	<0.2	0.03	<2	0.4	0.8	2	2	18
-3B	0.2	<0.2		2.0	1.8	1.9	11	230	<0.2	0.01	1.5	0.2	.9	2	4	18
ER2-1S	↑	↑	↑	1.7	6.8	2.4	11	180	1.4	.03	6.0	↑	1.2	↑	64	19
-1B				1.9	4.7	2.1	11	160	2.1	<.01	6.6		1.4		41	11
HR2-1S				2.1	5.0	2.0	10	220	<0.8	<.01	5.4		1.9		55	14
-1B				2.6	2.3	1.4	16	120	1.3	.04	4.1		<0.9		35	6
TN2-1S				2.0	4.2	1.8	11	140	1.6	.02	4.7		<0.9		35	15
-1B	<0.1	<0.2	ND	2.1	3.2	1.8	9	200	4.0	.02	3.0	1.0	<0.9	< 3	23	22
A -1S				0.3	3.2	0.8	7	52	2.4	.01	2.2		<0.9		23	10
-1B				0.6	5.1	1.0	8	67	2.9	<.01	3.2		<0.9		25	6
C -1S				0.5	4.7	1.2	8	67	1.0	.02	5.3		<0.9		46	21
-1B				0.5	3.4	0.9	9	54	0.8	.02	4.2		1.1		23	7
E -1S				0.3	4.4	1.3	10	61	1.3	<.01	5.7		<0.9		42	16
-1B	↓	↓	↓	0.5	1.1	0.6	5	60	1.9	<.01	2.0	↓	<0.9	↓	16	6

ND = Not Determined; Dis = Dissolved; Part = Particulate

TABLE 5. CORRELATION COEFFICIENTS BETWEEN PARTICULATE TRACE METALS, PARTICULATE PHOSPHORUS, AND CHLOROPHYLL *a*, NOVEMBER 1974

	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn	$P\text{-}PO_4$	Chl *a*
Cd	1.000	0.173	0.484	0.517	-0.413	0.535	0.392	0.737	0.286	-0.007
Cr		1.000	0.675	0.642	-0.344	0.402	0.589	0.415	0.720	-0.206
Cu			1.000	0.936	-0.842	0.863	0.873	0.784	0.906	0.176
Fe				1.000	-0.375	0.801	0.847	0.729	0.868	0.188
Hg					1.000	-0.764	-0.685	-0.636	0.029	-0.020
Ni						1.000	0.916	0.842	0.871	0.242
Pb							1.000	0.909	0.889	0.306
Zn								1.000	0.846	0.533

TABLE 6. CORRELATION COEFFICIENTS BETWEEN "SOLUBLE" TRACE METALS, PARTICULATE PHOSPHORUS, AND CHLOROPHYLL *a*, NOVEMBER 1974

	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn	$P\text{-}PO_4$	Chl *a*
Cd	1.000	-	-0.550	-0.664	0.295	-0.832	-	-0.409	-	0.581
Cr		1.000	-	-	-	-	-	-	-	-
Cu			1.000	0.622	-	0.470	-	0.135	-	-0.398
Fe				1.000	-	0.888	-	0.650	-	-0.748
Hg					1.000	-	-	-	-	-
Ni						1.000	-	0.802	-	-0.787
Pb							1.000	-	-	-
Zn								1.000	-	-0.543

TABLE 7. CORRELATION COEFFICIENTS BETWEEN PARTICULATE TRACE METALS AND CHLOROPHYLL *a*, APRIL 1975

	Cd	Cr	Cu	Fe	Ni	Pb	Zn	Chl *a*
Cd	1.000	0.584	0.498	0.670	0.800	0.882	0.818	-0.412
Cr		1.000	0.990	0.978	0.931	0.858	0.911	-0.105
Cu			1.000	0.973	0.913	0.879	0.906	0.276
Fe				1.000	0.956	0.916	0.920	0.267
Ni					1.000	0.937	0.945	0.128
Pb						1.000	0.941	-0.080
Zn							1.000	-0.093
Chl *a*								1.000

TABLE 8. CORRELATION COEFFICIENTS BETWEEN PARTICULATE TRACE METALS, PARTICULATE PHOSPHORUS, AND CHLOROPHYLL *a*, JUNE, 1975

	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn	$P\text{-}PO_4$	Chl *a*
Cd	-	-	-	-	-	-	-	-	-	-
Cr		1.00	.746	.848	.537	-	-	.113	.381	-.494
Cu			1.00	.884	.284	-	-	.560	.223	-.433
Fe				1.00	.280	-	-	.465	.095	-.452
Hg					1.00	-	-	.099	.062	-.524
Ni						1.00	-	-	-	-
Pb							1.00	-	-	-
Zn								1.00	.535	.128

TABLE 9. CORRELATION COEFFICIENTS BETWEEN "SOLUBLE" TRACE METALS AND CHLOROPHYLL *a*, JUNE 1975

	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn	Chl *a*
Cd	1.00	-	-	-	-	-	-	-	-
Cr		1.00	-	-	-	-	-	-	-
Cu			1.00	.186	-.167	.754	.408	.784	-.220
Fe				1.00	-.264	.502	.156	.440	-.322
Hg					1.00	-.497	-.359	-.505	-.387
Ni						1.00	.311	.878	-.036
Pb							1.00	.566	-.346
Zn								1.00	-.119

TABLE 10. MONTHLY FREQUENCY OF PHYTOPLANKTON FOUND IN NEW YORK HARBOR FROM NOVEMBER 1974 - APRIL 1978 AT ALONGSHORE AND MID-HUDSON RIVER CHANNEL STATIONS

New York Harbor Phytoplankton	1976-1978 Shore-Side Station												1976-1978 Off-Shore Station											
DIATOM SPECIES	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Amphiprora						x														x				
Amphora	x	x	x	x	x	x			x	x		x												
Asterionella japonica	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Bacteriosira fragilis	x	x	x	x	x				x			x									x	x		
Biddulphia alterhans	x	x	x		x			x		x										x	x	x		
B. aurita																					x			
B. granulata		x																						
Biddulphia sp.	x									x		x												
Cerataulima bergoni	x	x	x	x		x			x				x	x	x	x				x				x
Chaetoceros decepiens	x	x	x	x	x			x	x					x	x									
Chaetoceros sp.	x	x	x	x					x	x										x	x	x		
Corethron hystrix	x	x	x				x	x	x		x	x	x	x	x									

(continued)

TABLE 10. (continued)

New York Harbor Phytoplankton	1976-1978 Shore-Side Station												1976-1978 Off-Shore Station											
DIATOM SPECIES	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Coscinodiscus	x	x	x	x	x	x	x	x	x	x	x	x	x								x	x	x	x
Cymbella	x	x		x							x													
Ditylum Brightwellii		x	x											x	x					x		x	x	
Eucampia zoodiacus	x	x	x	x				x			x													
Fragilaria	x	x	x	x			x	x	x	x		x										x	x	
Grammatophora marina		x	x	x																				
Gyrosigma sp.	x		x	x	x				x	x		x											x	
Lauderia sp.														x	x									
Leptocylindrus danicus	x	x	x	x			x	x	x		x	x								x	x	x	x	
L. minimus		x	x	x																x	x			
Lichophora sp.			x	x						x	x	x												
Lithodesmium undulatum	x	x	x							x	x	x		x	x	x					x	x	x	x
Melosira nummuloides	x	x	x	x	x	x	x		x	x	x	x		x	x	x							x	x
Paralia	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x				x	x		x	x
Navicula	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x
Nitzschia closterium	x	x	x	x	x	x		x	x	x										x	x	x		
N. seriata	x		x	x	x	x	x		x	x		x		x	x	x					x	x	x	
Nitzschia sp.		x	x	x	x				x	x		x	x							x			x	x
Rhizosolenia delicatula						x																		
R. fragilissima		x	x			x	x					x											x	x
R. habetata	x	x	x																					
Rhizosolenia sp.	x	x	x	x									x	x									x	x
Skeletonema costatum	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Stephanopyxia sp.	x																						x	
Surirella sp.	x											x								x	x			
Thalassionema nitzschoides	x	x	x	x	x	x	x	x			x	x	x		x	x				x	x	x	x	x
Thalassionsira baltica	x	x								x		x										x	x	
T. condensata	x	x	x	x			x	x	x	x			x	x								x	x	x
T. hyalina	x	x	x	x							x		x		x	x							x	
T. Nordenskioeldii	x	x	x	x	x	x							x	x	x	x						x	x	
T. pseudonana	x	x	x	x	x	x	x	x	x	x	x	x			x	x				x	x	x	x	x
Thalassionsira sp.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x		x
Thalassicthrix longessema	x	x	x	x		x		x	x	x												x	x	x
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	MONTHS												MONTHS											

(continued)

TABLE 10. (continued)

New York Harbor Phytoplankton	1974-1978 Shore-Side Station												1976-1978 Off-Shore Station											
NON-DIATOM SPECIES	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Ankistrodesmus falcatus	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x		x	x	x	x	x
Ceratium tripos					x	x	x				x		x					x	x	x				x
Dictyocha		x	x										x					x	x	x	x			x
Dinobryon		x									x													
Dimophysis sp.	x									x	x									x	x	x	x	
Distephanum speculum		x	x	x									x	x		x								
Ebria tripartita	x	x	x	x	x	x			x				x	x	x	x	x			x	x			x
Eutreptia marina	x					x	x	x	x		x	x						x	x	x	x	x	x	x
Peridinium sp.		x	x									x							x	x				
Prorocentrum sp.													x							x	x			
Scenedesmus sp.	x	x			x	x	x	x	x	x			x			x	x			x	x	x	x	x
GENERAL DIVISIONS																								
NON-DIATOMS	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Chlorophyta	x	x				x	x	x	x	x		x	x					x	x	x		x		
Cyanophyta				x		x	x	x		x	x									x		x		
Dinoflagellata		x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	
Euglenophyta		x				x	x	x					x											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	MONTHS												MONTHS											

Figure 9 gives depth-averaged, mean monthly phytoplankton abundance at the Morton Street station for the entire study period. The trends defined by these data from 1976 to 1978, are in fairly good agreement with those of mid-channel transect stations represented by stations 1, 4, and 5 (Fig. 10). While species occurrence at alongshore stations is difficult to relate to general conditions in the estuary, total cell density seems to agree quite well. The use of depth and monthly averaging reduces the variability inherent in phytoplankton data to some extent, and overall seasonal trends evidenced in the estuary seem reasonably consistent. In general, cell densities and chlorophyll a (chl a) biomass decreased with distance into the estuary, away from the New York Bight Apex. (Table 11). Hence, in monitoring, it is necessary to compare stations within similar areas. Between station differences should be recognized and future efforts would be best served by con-

tinuing work at stations established in this study.

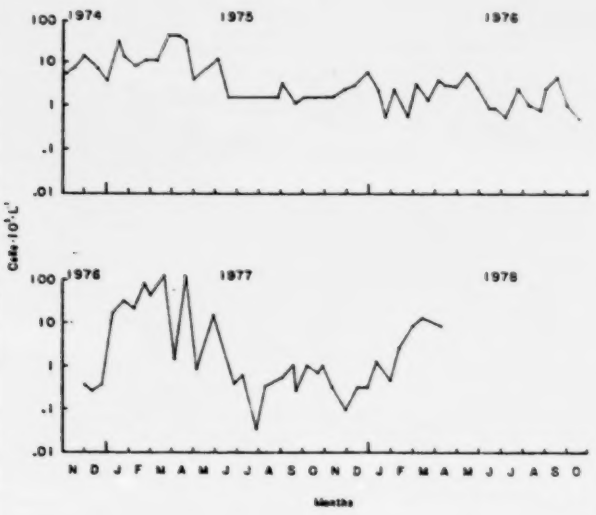

Figure 9. Depth averaged, mean monthly phytoplankton abundances (on logarithmic scale) at Morton Street, 1974 - 1978.

The high chl a in the East River may be indicative of a biomass loading from Long Island Sound. A station south of station E (at South Street) had biomass distributions similar to station 2.

Skeletonema costatum was the most common diatom in the estuary during this study. The abundance of S. costatum at the Morton Street station is shown in Figure 11. As with total phytoplankton, S. costatum evidenced variability in abundance. However, abundance of this species peaked between January and March, and decreased during the summer and fall. Abundance during summer 1977 was lower than in the preceding years. Figure 12 shows similar patterns at mid-channel stations.

Malone (1977a) suggested that the Lower Hudson Estuary may be unlike other estuaries where diatoms generally grow at higher rates (and might therefore be expected to be most abundant) during summer. Figure 13 shows that during summer, non diatoms composed the greater proportion of the phytoplankton. Orders of magnitude increases in S. costatum and other diatoms in future summers, therefore, may be indicative of changes in water quality. We discuss possible reasons why this does not occur at present in another section.

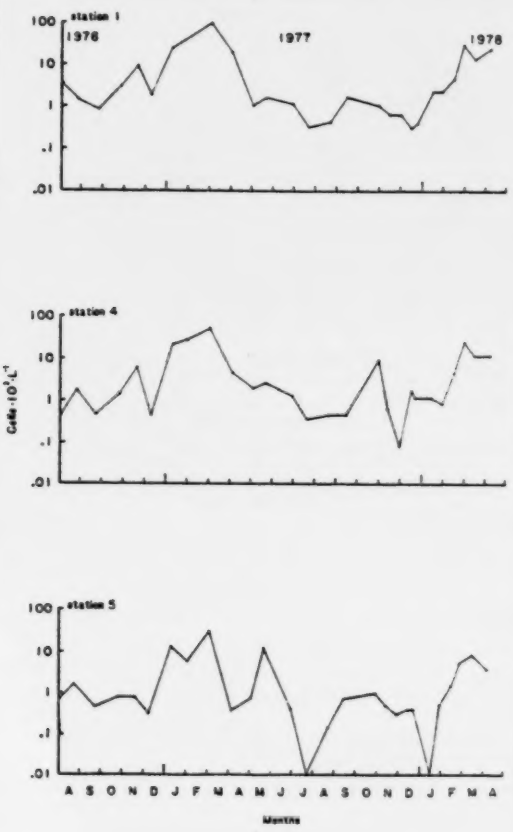

Figure 10. Depth averaged, mean monthly phytoplankton abundances at 3 stations in the mid-Hudson channel, 1976 - 1978. Upper: station 1; Middle: station 4; Lower: station 5.

Primary Productivity

Primary productivity has been measured by other workers (Steemann-Nielsen 1952; Malone 1977b; 1977c; O'Reilly *et al.* 1976) as well as ourselves and the trends described in the past are consistent with our own findings. Presented here is a summary of our work. Greater detail is available in Kleppel (1979).

Primary productivity at East River station E (Figure 14) (0.01 - 1.2 g $C \cdot m^{-2} \cdot d^{-1}$) exhibited a fall minimum (November), and a summer maximum (July). Secondary peaks (0.35 - 0.45 g $C \cdot m^{-2} \cdot d^{-1}$) occurred during the diatom biomass maximums in February - March. Chlorophyll normalized productivity (P/chl *a*) presented in Figure 14, gives an indication of the photosynthetic

activity of the biomass. P/chl a remained relatively low until May, when an increase began which terminated in a July maximum. Productivity and P/chl a values in the East River were lower, especially during the peak period, than those reported for Lower and Upper New York Bays by Malone (1977c) and O'Reilly et al. (1976), though all estimates on a per diem basis were within the same order of magnitude, and followed approximately the same seasonal patterns. One reason why our values were low compared with those of other workers may be that we incubated in situ whereas others used shipboard incubators. At any time of day, the shipboard incubation would give a constant light intensity to a sample under a given neutral density filter. In the East River during the winter, floating ice may cover samples for several hours at a time, and reduce light penetration and duration substantially. Inconsistent lighting may have significant effects on photosynthesis (Soeder and Stengel 1974).

TABLE 11. CELL DENSITY AND CHLOROPHYLL a DISTRIBUTIONS IN NEW YORK HARBOR, FEBRUARY 1978

Station	Cell Density (cells/ml)	Chl a (ug/l)
1	4,100	39
2	3,700	37
4	2,400	27
6	1,500	22
E	13,200	49

Over the period September 1977 to April 1978 primary productivity (P, $mgC \cdot m^{-2} \cdot d^{-1}$) was related to biomass (chl a) as $P = 8.73$ chl a + 24.5 ($r^2 = 0.88$; $p < 0.01$) (Fig. 15). However, from May - August 1978, the time of succession from a diatom-dominated flora to one composed primarily of chlorophytes and flagellates, productivity was higher than would be predicted by this relationship. The relationship between P/chl a and integrated photosynthetic light availability at this time decreased from one which explained 95% of the variance ($r^2 = 0.97$; $p < 0.01$) to one which explained 59% ($p < 0.05$). Further, the relationship between P/chl a and water temperature increased from $r^2 = 0.44$ to $r^2 = 0.72$ during the same period. The high summer P/chl a supports Malone's (1977c) hypothesis that a bloom (of nannoplankton) occurs in the estuary in the summer. The data seem to indicate that phytoplankton photosynthetic rates might be linked to temperature (more so than light) at this time. Despite relatively high productivity m^{-2} during February to March, (0.4 mg $C \cdot m^{-2} \cdot d^{-1}$) P/chl a was low due, apparently, to light limitation. Malone (1977c) proposed that during the winter productivity peak, phyto-

plankton growth rates are lower than the rate at which they are washed out of the estuary.

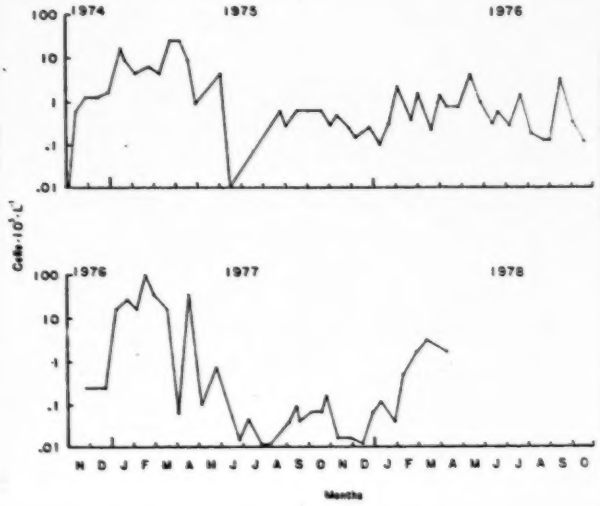

Figure 11. Depth averaged, mean monthly abundances of the diatom, Skeletonema costatum, at Morton Street, 1974 - 1978.

Laboratory Experiments

The question then arises as to why diatom growth in the estuary is low, especially during the summer when one would expect maximal values. Although diatoms are subdominant in the summer (10^3 - 10^4 cells·l^{-1}), they are nonetheless present. Furthermore, while silicate concentrations are lower during summer than winter, levels never fall to zero. Malone's (1977c) lowest SiO_3-Si measurement of 4.0 ug-at·l^{-1} in Upper New York Bay could support large diatom populations under optimal conditions. It was hoped that the laboratory work would provide some insight into these enigmas.

When the diatom, Skeletonema costatum, was grown in media composed of 90% sterile-filtered (CS) water from the South Street station obtained during February - March 1977 and 1978, under optimal light and temperature conditions, cells grew at rates of 1.4 - 1.6·d^{-1} (Fig. 16a). Photosynthetic rates of about 10^{-6} ug C·$cell^{-1}$·h^{-1} were observed (Fig. 17a), about 2 times higher than observed in the field (Fig. 17c). (This lends support to the hypothesis that the inhibitory substance(s) are apparently dissolved and that diatom growth and productivity are light limited during the winter-spring biomass peak.) (Samuels 1977, Kleppel 1977)

We have found that cold-sterilization of Harbor water is an effective technique for our assay work.With the addition of 10% and 50% enriched seawater, medium sufficient nutrients are available for growth, while permitting the assay of dissolved inhibitors.

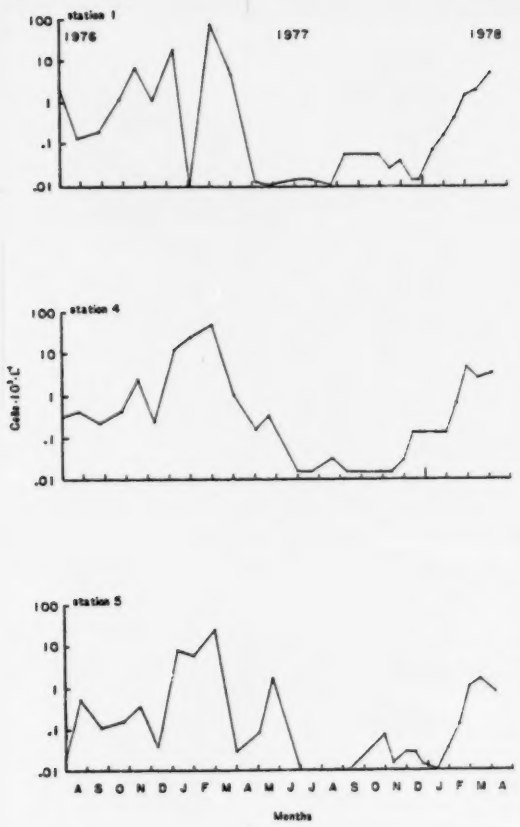

Figure 12. Depth averaged, mean monthly abundances of the diatom, Skeletonema costatum, at 3 mid-Hudson channel stations, 1976 - 1978.

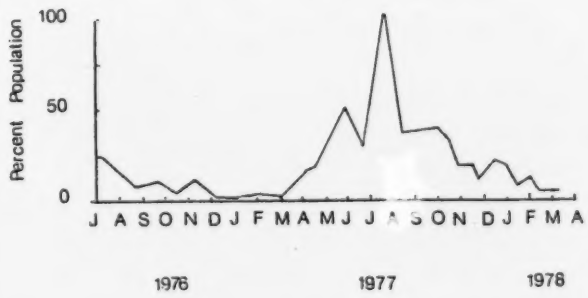

Figure 13. Monthly percentages of non-diatom to total flora averaged over all stations, 1976 - 1978.

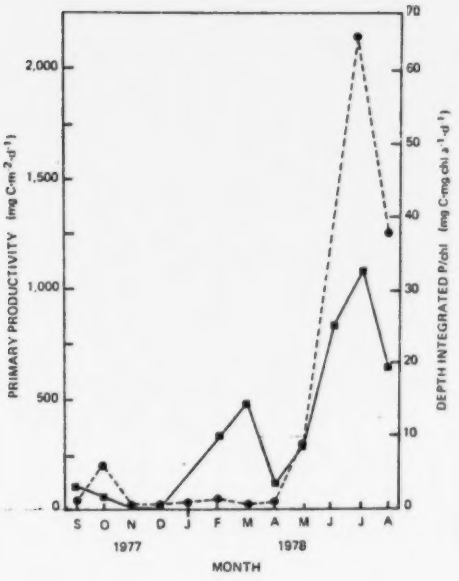

Figure 14. Depth integrated primary productivity per unit area (solid line), and per unit chl a (P/chl; dashed line), at station E, 1977 - 1978.

However, during spring-fall 1977 and spring (late April-early May) and fall 1978, optimization of light and temperature often did not result in high growth or production rates.

Further, dilution of water collected during summer and fall often resulted in an increase in growth rate. In July, rates increased from 0 (90% CS) to about $0.4 \cdot d^{-1}$ (Fig. 16a). Reducing the CS water to 10% gave a rate of approximately $0.8 \cdot d^{-1}$ at this time (not shown). This phenomenon did not occur at any other time of the year, and suggested that something about the medium might be inhibitory to diatom growth during summer-fall. When the medium was autoclaved, growth rates and productivity increased relative to the CS group. The same was true when the water was filtered and then autoclaved (Fig. 16b-c; Fig. 17b).

Halving the concentration of harbor water in media prepared with AUTO water sometimes gave similar or slightly higher growth rates, but never to the extent seen in CS water; dilution of AUTO or F/A water to 10% never gave higher growth rates than media prepared from 90% harbor water.

The recovery of diatom growth after treatment of the water argues for the presence of some inhibitor which can be volatilized or degraded by autoclaving.

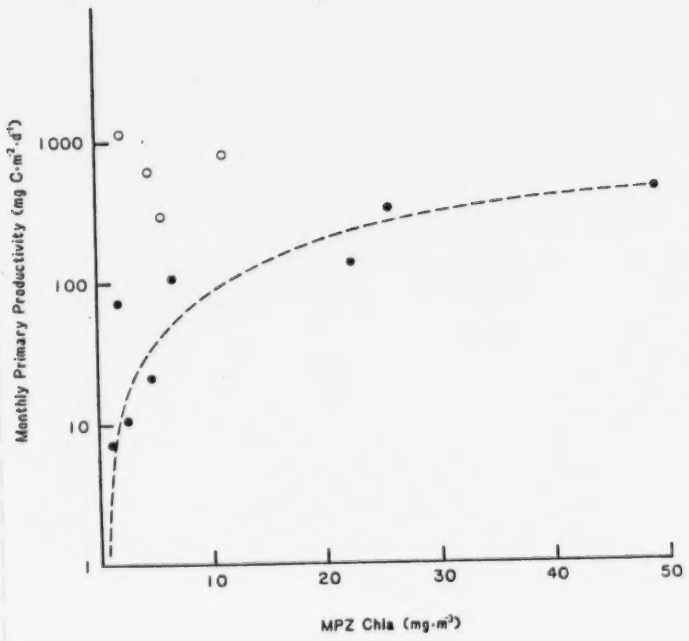

Figure 15. Regression of primary productivity (log scale) to mean photic zone chlorophyll a at station E, September 1977 - August 1978. The regression explains 88% of the variance ($p < 0.01$) when data from May - August (open circles) are deleted.

The other period of time when growth rates and photosynthesis were low, even under optimal light and temperature, occurred in the spring--usually between April and June. Dilution of CS water did not result in better growth; nor did autoclaving, or filtering and autoclaving.

In the spring, the abundance of S. costatum and the rate of silicate delivery to Upper New York Bay both decline sharply. Apparently, the washout of Si from the Harbor to the epicenter of the bloom in the Bight Apex is reduced in the spring, and this contributes to termination of the bloom (Malone et al. in press). While this does not relate directly to growth rates in the estuary, there would seem to be a link between Si-delivery, the bloom in the Apex, and diatom growth in the estuary.

As noted above, diatoms are always present in the estuary, and despite the declining Si concentrations, one would expect that the 10^3 - 10^4 diatoms·l^{-1} should exhibit relatively high growth rates under the increasing photoperiod at this time. The delivery rate of silicate during the low flow period (about 20 m tons·d^{-1}) to the Upper Bay, given in Figure 8, translates

to 1.9 ug-at $Si \cdot l^{-1} \cdot d^{-1}$ over the volume of the Bay. This is lower than the ambient levels in the estuary (4 - 10 ug-at $\cdot l^{-1}$) reported by Malone (1977) suggesting that Si accumulates and is not taken up by the phytoplankton. Using values for the maximum growth rate (u max) = $1.33 \cdot d^{-1}$ and half saturation constant (K_s) = 1.23 ug-at $Si \cdot l^{-1}$ derived empirically by Samuels (1979) it is possible to estimate a growth rate on the order of $0.8 \cdot d^{-1}$ from the above rate of Si-delivery. This clearly did not occur in the laboratory study despite the optimization of parameters (light and temperature) which are suggested in the literature as limiting phytoplankton growth in the estuary. However, when Si, PII trace metals (Provasoli et al. 1957) or vitamin B_{12} were added to the medium, growth proceeded well (Fig. 18).

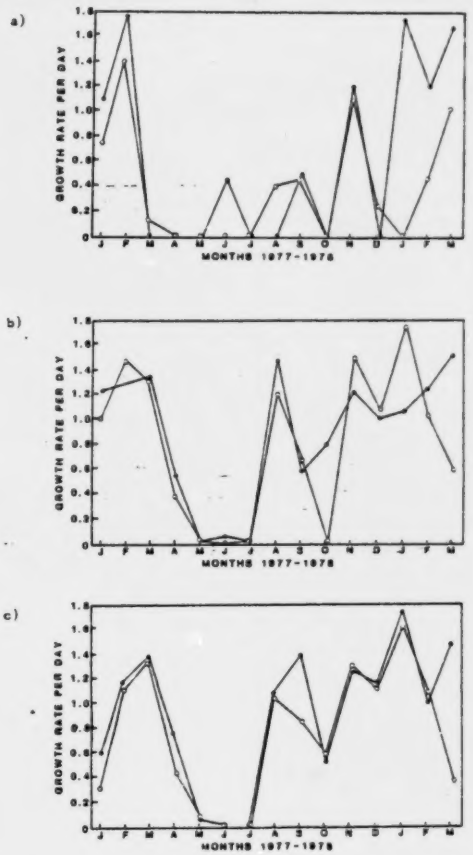

Figure 16. Growth rates of Skeletonema costatum in 90% and 50% treated East River water samples, January 1977 - April 1978.
a) Water was passed through a sterile, 0.22 um filter (CS).
b) Water was autoclaved (AUTO).
c) Water was filtered, then autoclaved (F/A).
Closed circles = 90%; Open circles = 50%.

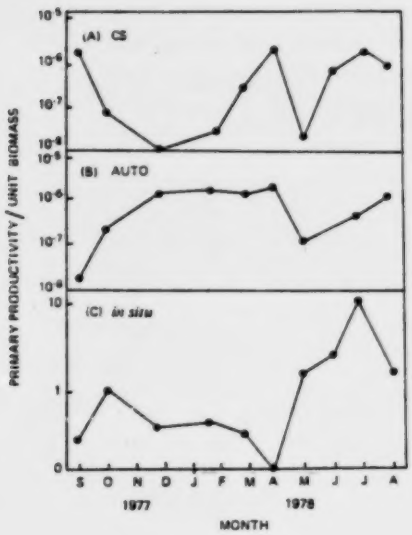

Figure 17. a) Primary productivity/cell of Skeletonema costatum in East River water passed through a sterile 0.22 um filter (CS).
b) As in a), but for autoclaved water (AUTO).
c) In situ productivity/unit chl a at station E, September 1977 - August 1978.

The interpretation of these results is difficult and must be considered as tentative, yet we suspect that the growth of diatoms in the estuary is influenced significantly by environmental stresses from suboptimal conditions and an array of toxic substances (O'Connors et al. 1978). It follows that the nutritional requirements of diatoms growing under these conditions could be substantially different from diatoms in pure or less contaminated media. The enrichment of the medium with certain growth stimulating factors may improve the overall physiological status of the cell and, as suggested in these studies, result in an increase in growth rate. As mentioned above, we present this interpretation with caution, and suggest the need for further study of the phenomenon. We note, however, that variations in nutrient uptake and growth rates in diatoms as a function interacting environmental factors are well documented (Soeder and Stengel 1974; Ferguson et al. 1976; Lane and Levins 1977). For instance, when sewage effluents were used to provide macronutrients (N, P, Si) in a medium, contaminants in the effluents apparently reduced photosynthesis and N-uptake rates below those obtained in sea water media enriched with reagent grade nutrients (MacIsaac et al. 1979).

The assays developed here can be used for future assessments of water quality. The growth of diatoms in the spring without addition of micronutrients, and in the fall, in untreated Harbor water, would be indicative of

reductions in stress.

Both the productivity assay (^{14}C) and the growth assay are relatively simple to conduct and require minimal space and cost for supporting test organisms. The ^{14}C-assay tends to be slightly faster than the growth rate assay, but the latter is less costly and requires no special equipment other than a compound microscope and a nannoplankton counting chamber.

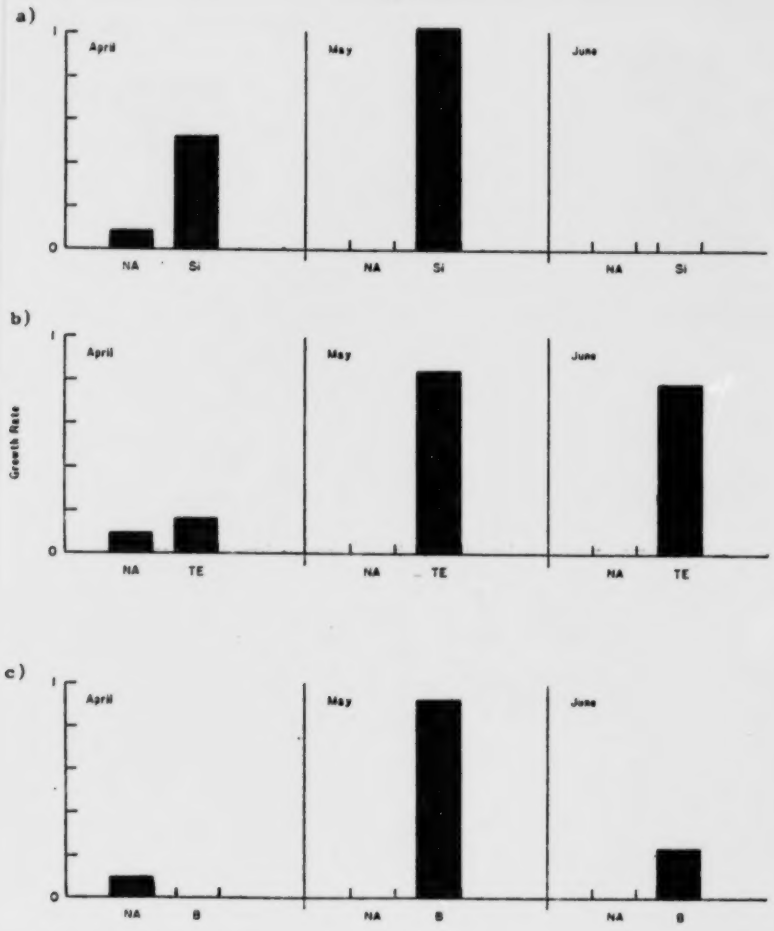

Figure 18. Growth rates of Skeletonema costatum as a function of nutrient additions to 90% sterile-filtered (CS) harbor water versus no addition (NA).
a) Addition of 0.04 ug-at $Si \cdot ml^{-1}$
b) Addition of PII metals mix (TE) (Provasoli et al. 1957)
c) Addition of 3 $ng \cdot ml^{-1}$ vitamin B_{12} (B)

Uptake and Toxicity of Metals

The metals tested (Cd, Ni, Pb, Fe) were usually concentrated rapidly by the phytoplankton used in the experiments. Uptake proceeded most rapidly in the first 16 hours of any experiment where approximately 70 - 75% of the metal initially added to the medium was present in the phytoplankton fraction.

Nickel uptake was exceptional in that it was taken up at fairly low rates. After 16 hours exposure, only 26 - 47% of the Ni added was detected in the phytoplankton.

Toxicity was assessed by exposure of phytoplankton to 0.5 and 0.1 ug/l of each metal for 2, 8, 16, and 48 hours. After exposure, cells were transferred to fresh, uncontaminated medium and incubated for 7 days. Cultures were then examined microscopically for loss of motility (in motile species) or the presence of morphological anomolies as indicative of toxicity. There was no difference between control and any of the experimental cultures with respect to these parameters.

Significance of Results to Prospectives for Improving Water Quality

Our initial hypothesis was that phytoplankton growth and productivity in the lower Hudson River estuary might be inhibited by toxic substances. Removal of these substances without simultaneously removing large amounts of nutrients, could foster massive phytoplankton blooms. Hence, the enormous outlays of capital required to effect improved waste water treatment would bring about only partial retrieval of water quality.

The growth of diatoms in the estuary appears to be affected by inhibition and stress induced by toxic substances during various times of the year. While reduced light penetration is important in limiting phytoplankton growth during winter-early spring, supplement of adequate light will induce significant growth, this is not the case during the period in late spring and fall.

During this period, when Hudson River flow is at an annual minimum, diatom growth in the estuary seems to be influenced either directly (by inhibition) or indirectly (by altering physiological requirements for nutrients) by dissolved toxicants. The summer bloom of nannoplankton in the estuary would be predicted by the work of O'Connors et al. (1978), Powers et al. (1977), Fisher and Wurster (1973) and others as a possible response to organic pollution. While the idea that nannoplankton growth exceeds netplankton growth in perturbed systems is open to much criticism (see Eppley 1979), this nonetheless seems descriptive of phytoplankton dynamics in New York Harbor.

It is significant that, while diatoms are present in the Harbor at all times, there is presently no time when diatoms grow there at rates indicative of a bloom. During the winter such growth would conceivably be stimulated by removal of particulates from the water column to increase light penetration (see below). This, however, could probably not be accomplished under a New York City-operated program since the major particulate loading derives from the north. The effect of solids removal on primary productivity can be approximated for the high flow portion of the year using the equation of

Ryther and Yentsch (1957):

$$P' = \frac{R}{k} \times Ch \times P(sat) \qquad (2)$$

where, P' = primary productivity, as mg $C \cdot m^{-2} \cdot d^{-1}$

R = relative photosynthesis as defined by Ryther and Yentsch (1957) from experiments measuring C-fixation rates at experimental light intensities/C-fixation rates at optimal intensity x hours per day/extinction coefficient, k, x day x meters depth,

k = white light extinction coefficients, per meter

Ch = chlorophyll a content of a well mixed column of water, as $mg \cdot m^{-3}$,

and, P(sat) = light saturated photosynthetic rate, as mg $C \cdot mg\ Chl\ a^{-1} \cdot h^{-1}$. Values from the literature were used to obtain P(sat).

Malone (in press) gave the relationship between total suspended solids (SS) and k as, k = 0.01 + 0.10 (SS) for the estuary. The parameters needed for estimating productivity (P') are provided and compared with measured productivity (P) values for period October 1977 - March 1978 in Table 12; there was a strong correlation between P and P' ($r = 0.98$; p 0.001). The values of P" represent estimated primary productivity under half the solids load. Although a doubling of production would be expected for the estuary, the impact of this additional biomass in terms of removing N and P would be negligible.

Primary productivity during summer appears not to be as dependent upon light intensity as during the winter; and predictions based on Chl a and light data are not feasible (Kleppel 1979). However, any increased organic production during the summer would likely be translated into increased BOD.

It is therefore essential that efforts to improve water quality be undertaken with extreme caution and in conjunction with an intensive monitoring program. Our work has resulted in the production of two monitoring tools. First, we have established a baseline for phytoplankton abundance and species composition for alongshore stations in the Harbor. It would appear that the abundance of Skeletonema costatum, and other diatoms, as well as the presence of dinoflagellates can provide an indication of changes in water quality. The establishment of a permanent station in the Hudson River, at Morton Street can provide data indicative of water quality in Upper New York Bay. Order of magnitude increases (10^5 - 10^6 cells/l) in S. costatum abundance during summer would be considered evidence of water quality improvement. The presence of dinoflagellates at this time would suggest that the improvements are having the negative effect we would predict from removal of toxic substances without adequate nutrient removal. That is, growth inhibition is decreasing, and the potential for noxious blooms is increasing. This is reflective of the fact that for over 12 years dinoflagellate blooms have been documented

in Lower New York Bay, but have never been accompanied by simultaneous blooms in the Upper Bay (Mahoney and McLaughlin 1977).

TABLE 12. PARAMETERS REQUIRED FOR ESTIMATING PRIMARY PRODUCTIVITY (P') AND MEASURED AND ESTIMATED PRODUCTIVITY (P AND P') IN THE EAST RIVER, OCTOBER 1977 - MARCH 1978. ALSO ESTIMATED PRODUCTIVITY AS A FUNCTION OF HALVING SUSPENDED SOLIDS IN THE ESTUARY

Month	SS	k	R	P(sat)	Ch	P	P'	P"
October	8.2	0.83	14.9	2.8	1.39	78	69.9	138.1
November	20.4	2.05	10.5	2.8	1.03	7	14.8	29.4
December	18.6	1.87	11.6	1.5	1.89	13	17.6	35.0
January	24.6	2.47	10.0	1.5	2.33	18	14.1	28.2
February	12.2	1.23	13.0	1.5	25.77	336	408.5	817.0
March	23.7	2.38	17.3	1.5	49.20	449	536.4	1072.8

SS = suspended solids ($mg \cdot l^{-1}$)

k = extinction coefficient/meter

P(sat) = light saturated photosynthetic rates ($mgC \cdot mgChl\text{-}1 \cdot h^{-1}$), using values from Steemann-Nielson and Hansen (1959)

ch = $mgChl\underline{a} \cdot m^{-3}$

Units of productivity = $mgC \cdot m^{-2} \cdot d^{-1}$

The second monitoring tool, which has been provided is the assay using S. costatum as an indicator organism. The ability of S. costatum to grow in CS water during summer - fall would be indicative of improved water quality.

These tools can be utilized at minimal expense, and we recommend their incorporation into any management strategy. It is noted that monitoring the system will be a negligible portion of the cost of the total water pollution abatement project. At this point, the sources, identities, and concentrations of inputs to the estuary cannot be completely accounted for, because combined storm-sanitary sewering prevents adequate source control. The cost of amelioration of this situation is apt to be staggering. Although a care-

fully controlled restoration of New York Harbor water quality is a commendable goal, it is probably not feasible at this time. Our data suggest that due to the existence of many unknowns in the system, attempts to provide partial solutions to the problem could prove to be more detrimental than doing nothing at all.

SECTION 6

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SECTION 7

APPENDICES

APPENDIX I

TIME SERIES DATA FOR MID-HUDSON RIVER CHANNEL

Physico-chemical parameters for which time series data are presented for the period September 1976 - April 1978 are:

AI-1 Temperature (^{o}C)

AI-2 Dissolved oxygen (ppm)

AI-3 Ammonia-N ($ug\text{-}at \cdot liter^{-1}$)

AI-4 Nitrite-N ($ug\text{-}at \cdot liter^{-1}$)

AI-5 Nitrate-N ($ug\text{-}at \cdot liter^{-1}$)

AI-6 Total phosphorus ($ug \cdot liter^{-1}$)

AI-7 Ortho-phosphorus ($ug \cdot liter^{-1}$)

Each parameter is presented as the monthly, depth-averaged value. From left to right, top to bottom, stations are arranged as follows:

stations 1, 2

stations 3, 4

stations 5, 6

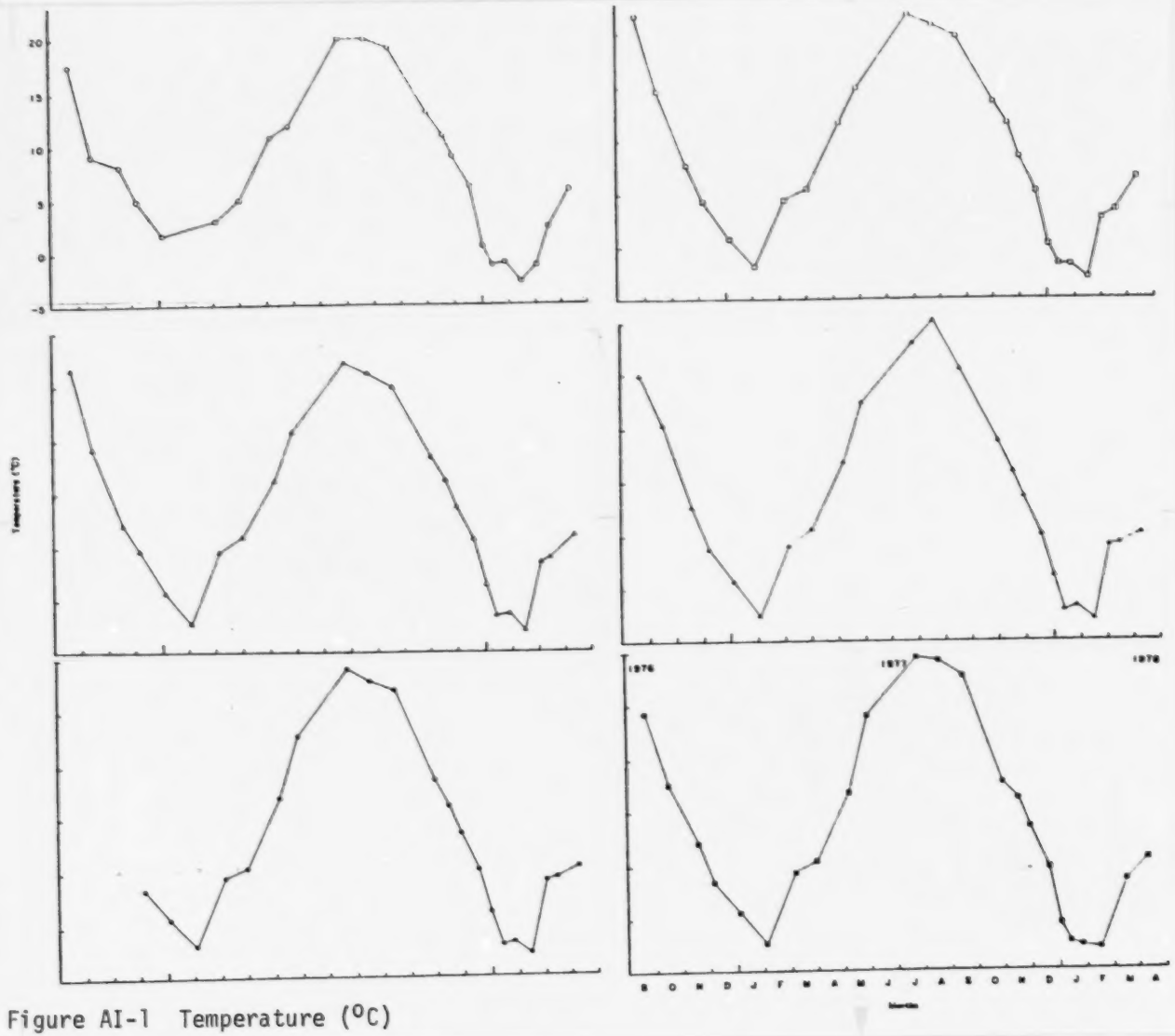

Figure AI-1 Temperature (^{o}C)

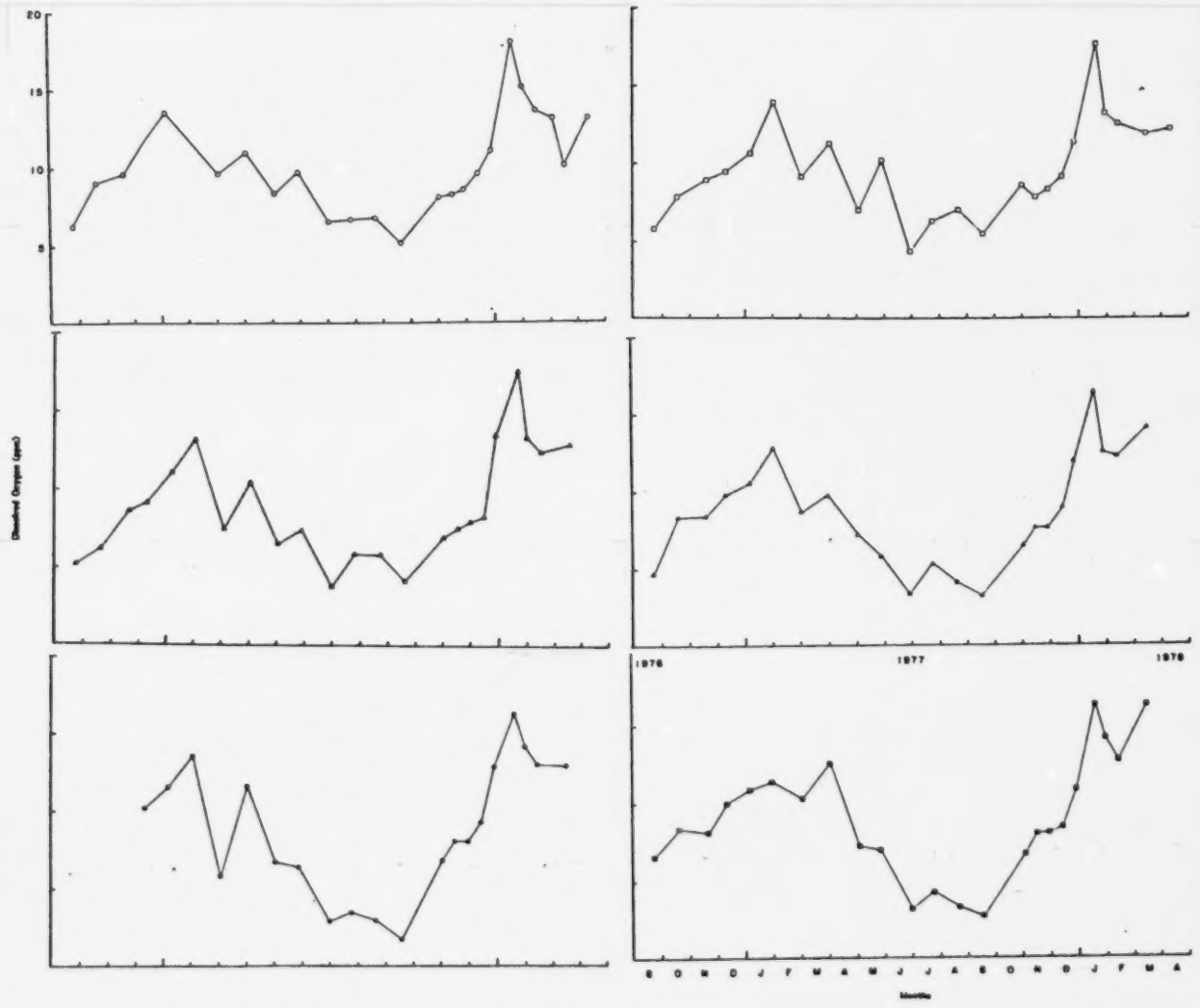

Figure AI-2 Dissolved oxygen (ppm)

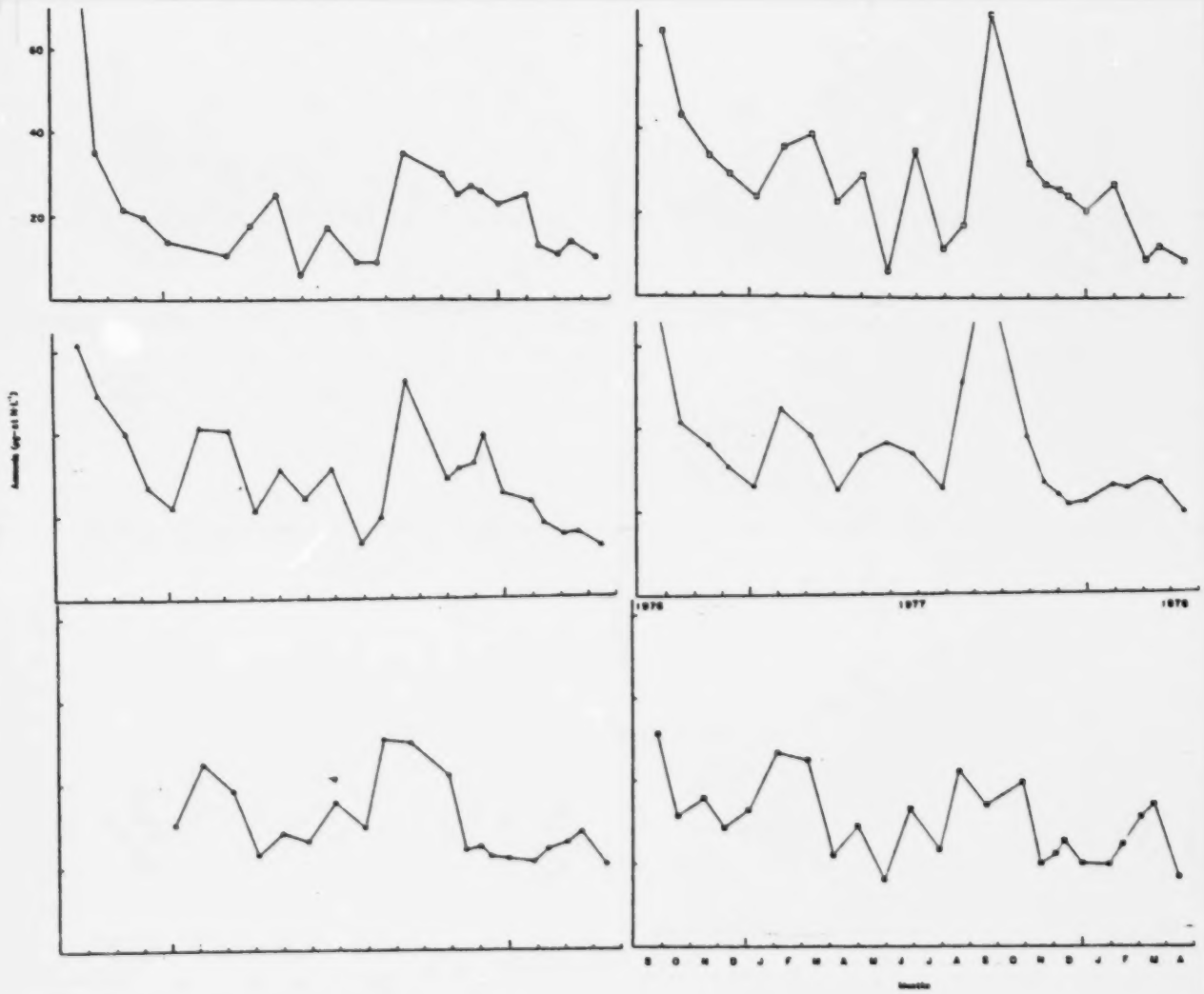

Figure AI-3 Ammonia-N (ug-at·liter^{-1})

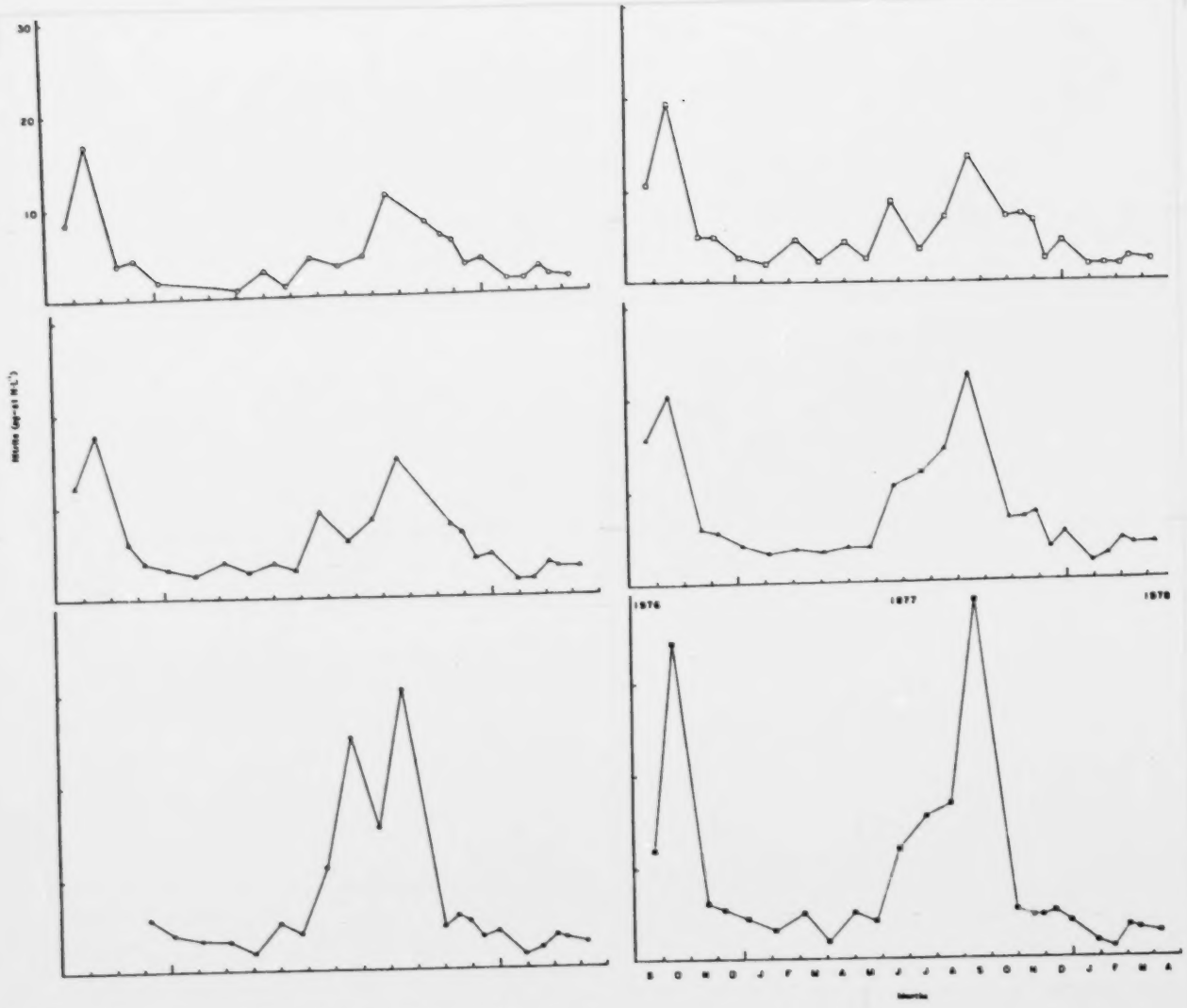

Figure AI-4 Nitrite-N (ug-at·liter^{-1})

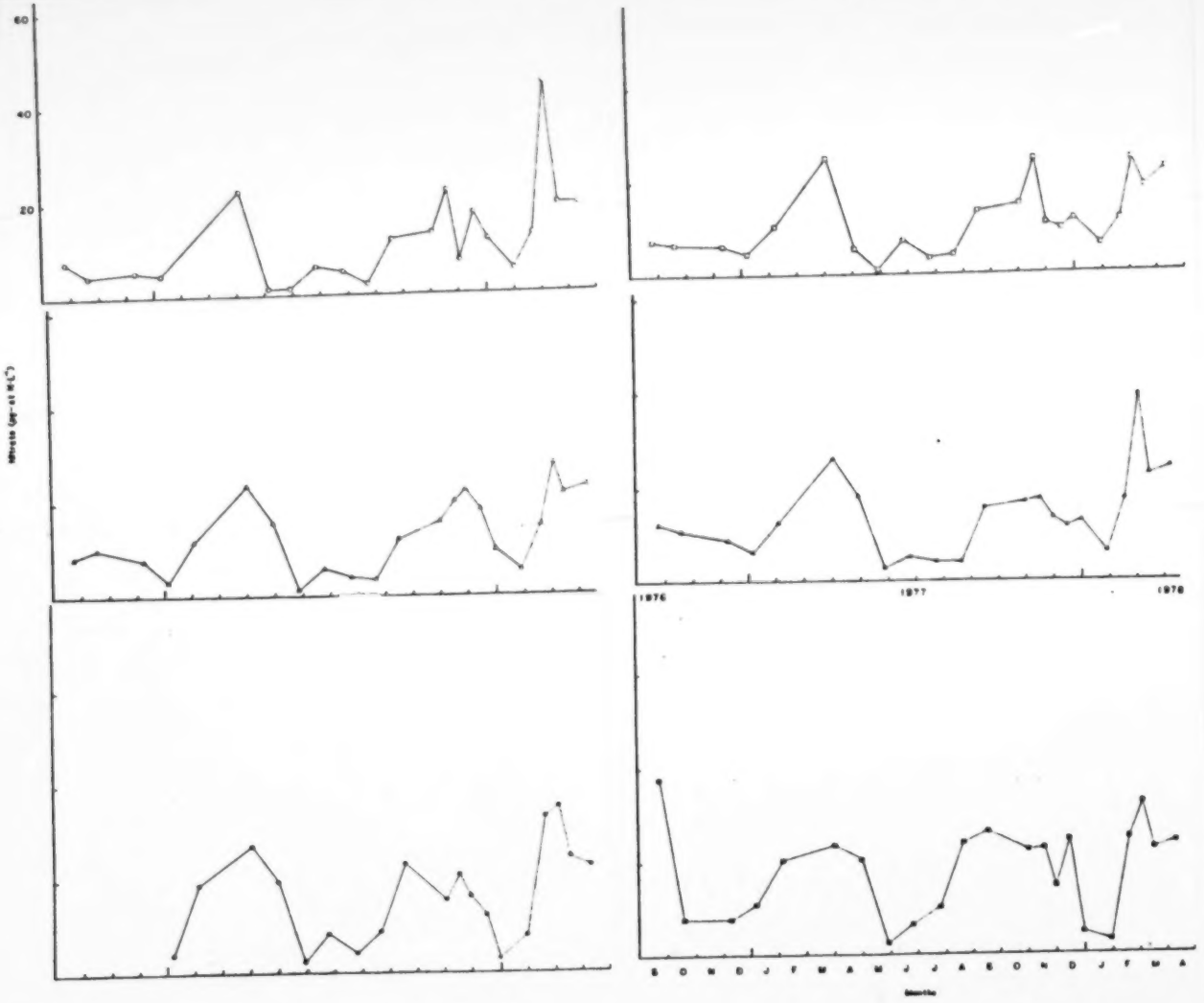

Figure AI-5 Nitrate-N (ug-at·liter^{-1})

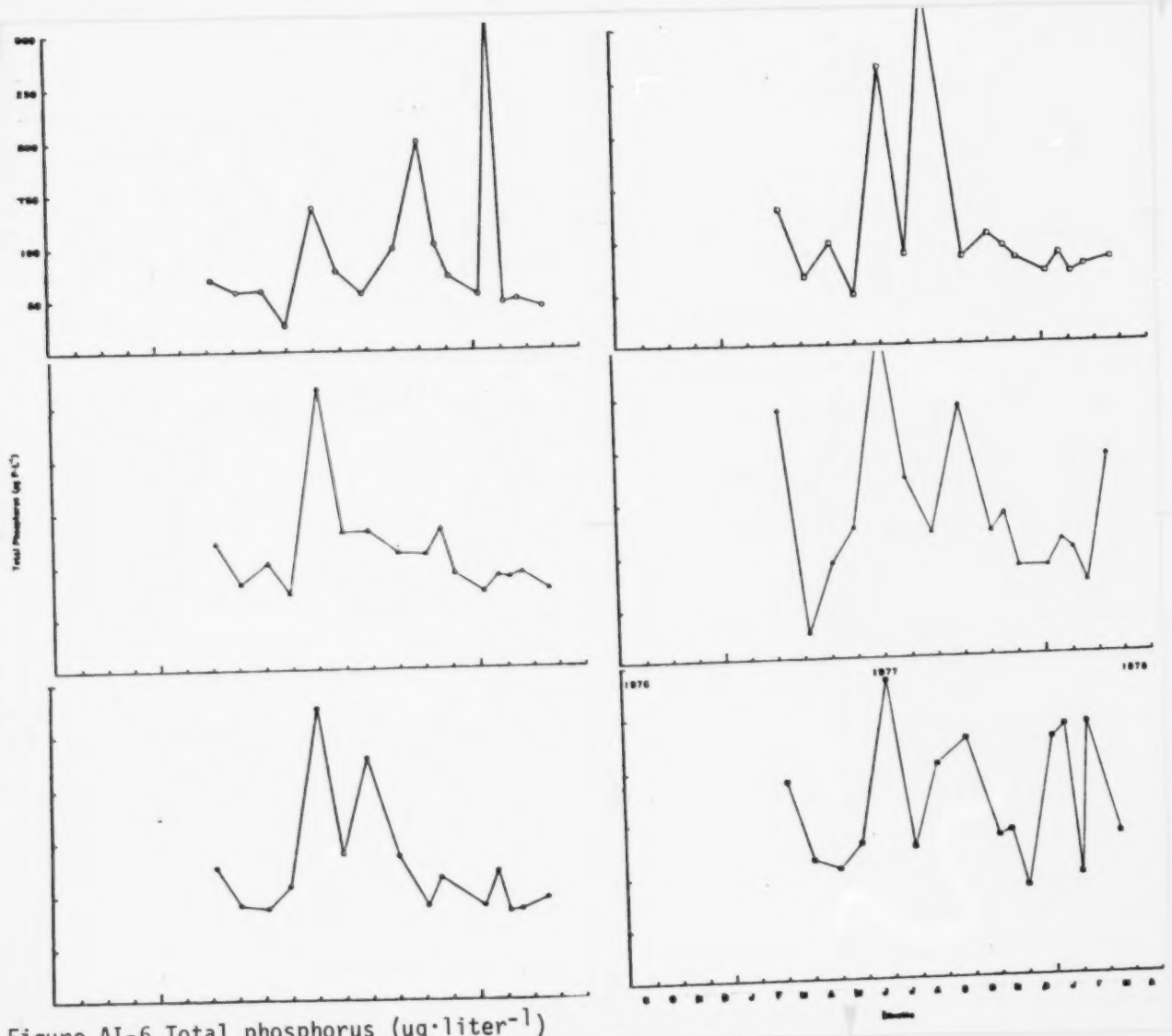

Figure AI-6 Total phosphorus (ug·liter^{-1})

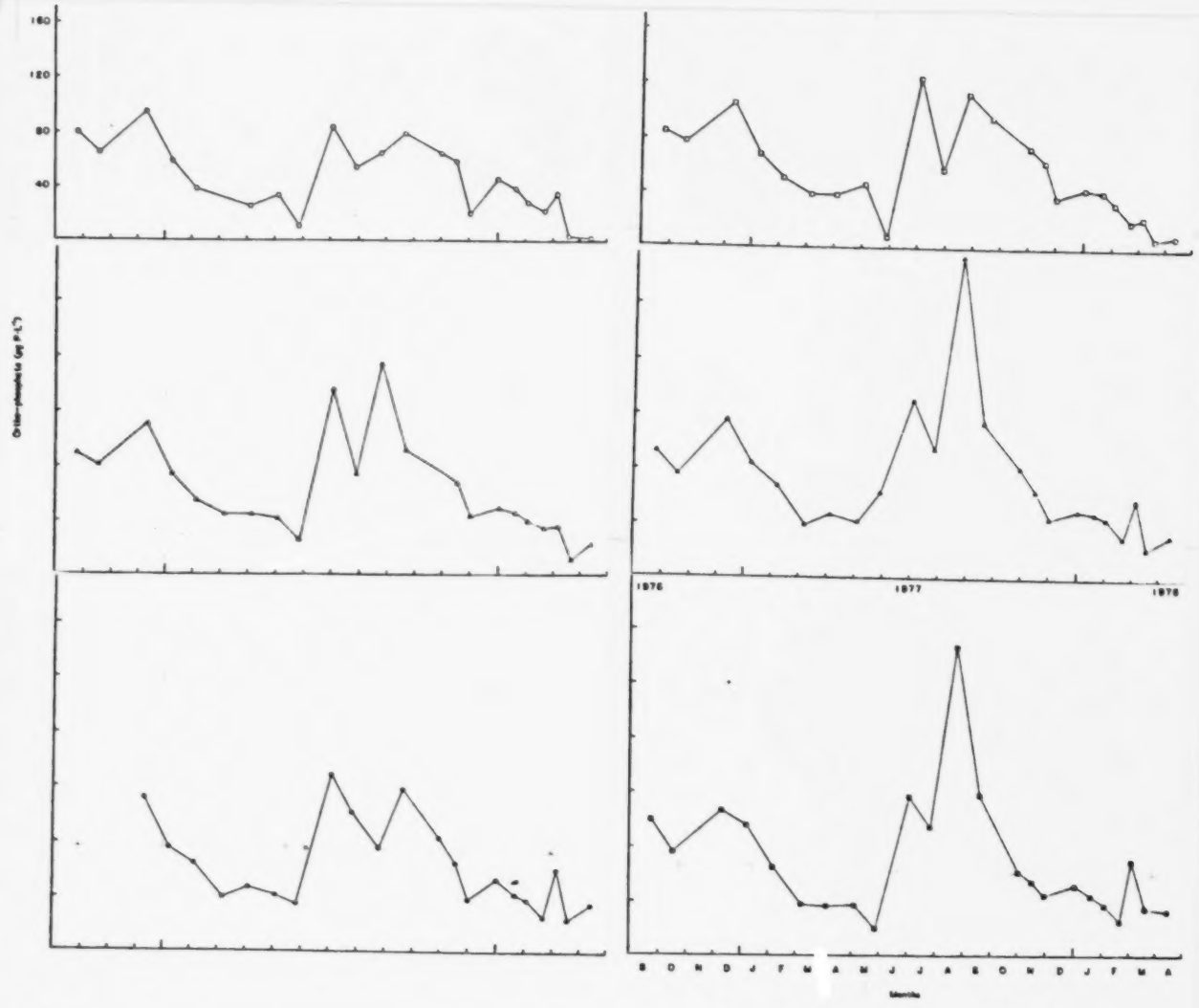

Figure AI-7 Ortho-phosphorus (ug·liter^{-1})

APPENDIX II

HYDRODYNAMIC MODEL FOR NEW YORK HARBOR UNDER CONDITIONS OF LOW HUDSON RIVER FLOW

One of the objectives of this project was to develop a model of hydrodynamic processes in New York Harbor. This has been accomplished for the low Hudson River flow period primarily through the efforts of Dr. M. P. Brown. Data from the mid-Hudson channel sampling program during 1976 - 1978 were used for calibration.

The model simulates the fate of algal nutrients in the lower Hudson estuary as a function of water mass movements. Results of simulations have been incorporated into the body of this report. However, since the thrust of our work has been to describe the dynamics of the phytoplankton in an empirical sense, it was decided that a separate appendix would be the most appropriate way for Dr. Brown to present a complete discussion of the model.

HYDRODYNAMIC MODEL FOR NEW YORK HARBOR

A corollary objective of this project was to employ the knowledge of New York Harbor phytoplankton dynamics, gained through investigation, to predict the response of the photoplankton to changes in wastewater quality that could result from upgraded sewage treatment. Within the proposed study framework this task appeared reasonable. A mathematical description of the processes affecting phytoplankton concentration in a defined Harbor volume including the interrelationships between wastewater constituents and phytoplankton could be validated and applied to hypothetical changes in wastewater loading of these constituents. Such model systems developed for freshwater lakes range in complexity from completely mixed systems with trophic state predicted by phosphorus loading (e.g. Vollenweider 1974) to three dimensional systems with multifactor regulation of several chlorophyll pools (Thomann and Segna 1980). These approaches satisfy a variety of water quality management needs ranging from the ability to generally describe the behavior of many lakes to the response of a specific water body. An approach analagous in simplicity to Vollenweider's lake model is nonexistent for estuaries due to the complexity of physical processes and the multiple factors which tend to regulate phytoplankton production in estuaries.

During the course of study it became apparent that transport of coastal phytoplankton from the New York Bight rather than primary production in New York Harbor controls the harborwide phytoplankton distribution (Malone 1977a). Fresh water phytoplankton are relatively insignificant throughout the year. The washout of the spring bloom of Melosira (= Skeletonema costatum) from the Hudson River is observed with regularity in samples taken at the George Washington Bridge in late spring.

Blooms of marine phytoplankton species generally do not originate in New York Harbor but do occur in Raritan Bay and the New York Bight Apex. The 1976 Ceratium tripos bloom which resulted in anoxic conditions in the New York Bight was of little consequence to New York Harbor. An excessive bloom of Coscinodiscus radiata during summer 1978 formed floating mats in local areas of Raritan Bay but was not evident on a harborwide basis. There appears to be no phytoplankton species endemic to the Harbor. Rather, the predominantly coastal population often reflects the distribution of organisms in the New York Bight Apex. Maximum phytoplankton concentrations were found at a station in the Bight Apex throughout the study and decreased towards the Harbor. The importance of phytoplankton advection from the Apex becomes particularly evident in linear salinity-phytoplankton concentration relationships during bloom periods (Belton 1979, Malone 1977c).

Malone (1977) employed a mass balance on the surface layer (5m) of the Upper Bay to explain the lack of accumulation of phytoplankton in the Upper Bay. Using this approach he concluded flushing rates were greater than

growth rates and therefore blooms are not likely to occur in the Lower Hudson estuary. Although certain assumptions inherent to his mass balance are questionable (i.e., he employs a Pritchard (1969)-type calculation of total surface flow but does not consider a loading of cells from upstream while the loading of salt from upstream is implicit to the calculation), his overall conclusion appears tenable.

Our work and that of Malone have demonstrated light rather than nutrient availability limits phytoplankton growth in the estuary during part of the year. Inorganic nitrogen and phosphorous are available in the Harbor throughout the year well above limiting concentrations. Light extinction within the Harbor is primarily a function of non-phytoplankton solids derived presumably from upstream distributed sources. However, Samuels (1979) indicates that at times the lack of trace requirements and possibly, the presence of inhibitory substances may limit phytoplankton production within the Harbor. Our work and recently that of Malone et al. (1980) have indicated silicates may limit the extent of the late winter-spring diatom bloom in the Bight Apex.

If phytoplankton growth rates do not exceed dilution rates in the lower estuary, consideration must be given to those factors that maintain depressed growth rates relative to dilution rates in the estuary in addition to those factors that regulate the growth of phytoplankton in the Bight Apex and hence the phytoplankton supply to the estuary.

One might expect the location of maximum phytoplankton productivity to be in the area where light limitation has been substantially reduced due to the settling or dilution of suspended solids (in addition to the dilution of possible chemical inhibitors) and where there yet exists an ample supply of nutrients. Maintenance of high productivity in the area would require rapid internal nutrient cycling or nutrient influx balancing or exceeding nutrient use and advective losses of phytoplankton. This area of maximum productivity appears to be located in the Bight Apex.

The primary productivity of the New York Bight has been the subject of study by Malone (1976, 1977a, b). His work has indicated primary production generally increases landward towards the Bight Apex. Our work has shown that, within the estuary, phytoplankton biomass increases towards the apex as well. Generally, the highest measured primary productivity was observed by Malone at a position near our Station 1. Therefore, with respect to modeling phytoplankton in New York Harbor, it becomes all important to be able to describe transport between the New York Bight and the Harbor in addition to the growth of phytoplankton in the Bight. There is little doubt the loading of nitrogen and phosphorus, much of which is derived from waste water discharge to the Hudson River, is responsible for maintaining elevated levels of primary production in the Bight Apex.

With respect to predicting the impact of nutrient loading reductions from advanced sewage treatment on the phytoplankton in the New York Harbor receiving waters it becomes of paramount importance to be able to describe the dynamics of growth and transport of phytoplankton in the New York Bight Apex, the seasonal boundary of the New York Harbor and our study area. In

terms of developing a mathematical model to aid in the analysis, a rigorously simulated boundary condition or the description of much larger geographical system than New York Harbor including an oceanographic system would necessarily have to be linked.

In models of the Potomac (Thomann et al. 1974) and Chesapeake (Salas and Thomann 1978) estuaries, sewage derived nitrogen and phosphorus were shown to stimulate phytoplankton growth in the immediate receiving body. The phytoplankton in turn significantly reduced soluble nutrient concentrations. In both systems, maximum phytoplankton concentrations are found within the described estuarine boundaries. Phytoplankton concentrations during summer greatly exceed those found in New York Harbor. To examine the relationship of wastewater loading to the distribution of inorganic nitrogen and phosphorus and to assess the impact of phytoplankton on their distribution during low flow conditions, a one-dimensional steady-state mathematical model of the lower Hudson Estuary and New York Harbor was developed.

A one dimensional approach does not reproduce the two layer nontidal estuarine circulation within the Hudson River Estuary (Abood 1974) but is adequate to reproduce the salient large scale circulation characteristics affecting the distribution of sewage derived nutrients and places less stringent demand upon data for calibration. Steady-state models for several flow regimes have been developed for the lower Hudson Estuary by Hydroscience (1975). One-dimensional models have been applied to the Hudson River Estuary by O'Connor (1962, 1966, 1972), Hydroscience (1978), and Thatcher and Harleman (1972). Salas and Thomann (1978) have applied this type of model to the Chesapeake system where Thomann et al. (1974) have applied a one-dimensional estuarine model for a water quality analysis of the Potomac Estuary.

The steady-state one-dimensional estuarine model equation with a decay term for a non-conservative substance is:

$$0 = \frac{Q}{A}\frac{dS}{dx} + E\frac{d^2S}{dx^2} - KS \qquad (1)$$

where Q is the freshwater flow rate (dimensions: length^3 time^{-1}).

A is the cross sectional area (dimensions: length^2).

E is the tidal dispersion coefficient (dimensions: length^2 time^{-1}).

S is the concentration of non-conservative substance (dimensions: mass length^{-3})

K is a first order reaction coefficient (dimensions: time^{-1}).

x is the horizontal distance (dimensions: length).

Equation 1 was solved for the Hudson River Estuary using a finite section approach (Thomann 1972) in which mass balances are developed around individual segments of the system and the resulting system of simultaneous

algebraic equations is solved.

The lower Hudson River and its plume from Haverstraw Bay to the Ambrose channel off Sandy Hook New Jersey were divided into forty-one consecutive segments (Figure AII-1). The Harlem and East Rivers, Kill Van Kull, Raritan Bay, and Jamaica Bay were not included in the segmentation scheme although waste inputs to these receiving bodies and their freshwater contribution were considered in the model as entering the appropriate adjacent segments. This simplification does not affect the large scale characteristics of the model, indeed, advection and dispersion terms in previous low flow models (Hydroscience 1975) for interfaces with these water bodies are substantially lower than in the plume of the Hudson. Employing forty-one consecutive segments accommodated the solution of the resulting forty-one simultaneous algebraic equations. The 41 by 41 tridiagonal advective-dispersive coefficient matrix was the practical upper limit for inversion on a 48 K desk top computer using an APL operator. The segment lengths, interface areas, and segment volumes necessary for the development of the finite difference weighting relationships, dispersive and decay terms were obtained from Hydroscience (1975) for segments 1-31 and from NDAA charts 369 and 12335 for segments 32-41 with consideration for their effect upon the calculative stability of the model.

Figure AII-1. Segments for model.

Estimates of dissolved inorganic nitrogen (DIN), ammonia and orthophosphorus loading via raw, primary and secondary sewage effluents were assigned to appropriate segments based upon data assembled by Mueller et al. (1976). Loadings for the model are summarized by reaches in Table AII-1. The area

of most intensive loading is the Upper Bay (Battery-Narrows) which received 70 metric tons/day of DIN and 14.4 metric tons/day of orthophosphorus. Approximately 70 percent of nutrient loading to the Upper Bay is here considered to be input from the East River.

TABLE AII-1. NUTRIENT LOADING AND TIDAL DISPERSION COEFFICIENTS BY REACH FOR STEADY STATE MODEL.

Model Segments	Total Raw Primary & Secondary Waste Flow cfs	Ortho-P Loading Metric tons/day	DIN Loading Metric tons/day	NH_3 Loading Metric tons/day	Tidal Dispersion E mi^2/day
1-7	10.3	.07	0.34	.33	11.6
8-13	67.8	.46	2.26	2.18	13.8
14-15	0	0	0	0	15.6
16-18	136.5	.93	4.55	4.41	17.5
19-23	38.2	.26	1.27	1.23	18
24-31	318.9	2.18	10.64	10.29	20
32-36	2100	14.38	70.04	67.78	20
38-41	739.7	5.06	24.67	23.87	20

Discharge from the Hudson River, the most important source of freshwater to New York Harbor, is highly variable with approximately half of the annual runoff occurring during March, April and May (Giese and Barr 1967). The calculation of freshwater input to New York Harbor is critical to understanding the water quality of the area (Jay and Bowman 1975). The relationship of Hudson River flow at the USGA Green Island gaging station at Troy, New York, the nearest nontidal gaging station on the Hudson, to flow entering New York Harbor has been addressed by among others Ketchum and Redfield (1951), Jay and Bowman (1975), and Hammond (1975). In relative terms, the lag time in water flow response from Green Island to New York Harbor decreases with increasing flow. Although Hammond (1975) has addressed the problems of lag time and incremental flow from the watershed below Green Island using analyses based upon "piston" velocity (lacking wave formation), there is presently no available analytical tool to provide fresh water input data for New York Harbor for a given date. The model developed here assumes a 5,000 cfs gaged flow at Green Island. Under prolonged low flow conditions with few fluctuations, freshwater input to New York Harbor can be reasonably estimated. Such conditions are met for flow data during summer 1977. The mean monthly

discharge statistics for July and August, 1977 at Green Island were 5,735 cfs and 5,439 cfs and 5,439 cfs, respectively (USGA 1978). Maximum and minimum flow rates for the month of August were 7,860 cfs and 3,320 cfs, respectively. Low flow conditions at Green Island continued through the first fourteen days of September with an average of 4,508 cfs during this period. A sudden increase in flow, averaging 12,838 cfs, due to a large precipitation event, was observed over the next five days and generally continued to increase through September.

The data used for model calibration and analysis are from seven stations along a mid-channel transect of New York Harbor from the George Washington Bridge to the Ambrose Channel off Sandy Hook, New Jersey, sampled August 22, 1977 and September 19, 1977 during the low flow period. Stations along the transect were generally sampled within one hour of high water slack on these two dates.

Finite section solutions for nitrogen and phosphorus loading as conservative substances were obtained by multiplying the steady state response matrix (Thomann 1972) calibrated with salinity data by a vector of loading rates for each segment and whose first and last elements included boundary conditions. Transformation terms were included in the principal diagonal of the tridiagonal matrix which was then inverted to solve for non-conservative substances. The seaward boundary conditions for salinity and nutrient concentrations were set on the basis of data collected at the most seaward station on the transect. The upstream boundary conditions were set on the basis of data and trends indicated for previous years in Garside et al. (1976), Simpson et al. (1975) and the USGS (1974).

The model was calibrated with salinity data by tuning tidal dispersion coefficients. The tidal dispersion coefficients that gave the best calibration are within the range of previously reported dispersion coefficients for the modeled area (Hydroscience 1975). The model's calibration fit to the vertical range of salinity data at each station for the August and September sampling dates appears in Figure AII-2.

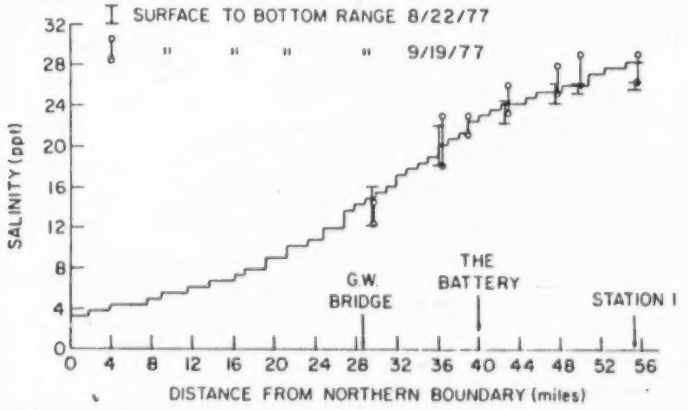

Figure AII-2. Calibration fit to vertical range of salinity data at each station for August and September.

An analytical method for evaluating the presence of sources or sinks of a nonconservative substance in an estuary was presented by Liss (1976). The method exploits the mixing and gradients of freshwater and seawater occurring within estuaries by interpreting a plot of the concentrations of a known conservative substance using salinity as abscissae and the concentrations of suspected nonconservative substance as ordinates. A linear relationship through end points of such a plot with salinity as the conservative substance should represent conservative behavior of the compared substance. The presence of data above this line indicates that sources of the substances exceed sinks in the estuary. Conversely, data below the line indicate the predominance of sinks over sources within the estuary.

This method has been employed by Simpson et al. (1975), Garside et al. (1976), Hammond (1975), and Ingram (1979) to interpret nutrient distributions in the Hudson River Estuary. Their analyses qualitatively linked the sewage load source of phosphorus and nitrogen to their distribution with salinity in the estuary. While Liss' (1976) method does permit analysis of the relative importance of sources to sinks, it does not permit one to examine sources or sinks individually. Indeed, linear relationships in such plots for a given nonconservative substance could indicate conservative behavior or the balance of sources and sinks in a highly reactive system. The data for nutrient model solutions is presented in this format (Figures AII-3b, 4b, 5b) to illustrate the quantitative link of sewage loading internal sinks and advective-dispersive processes to observed nutrient and salinity distributions.

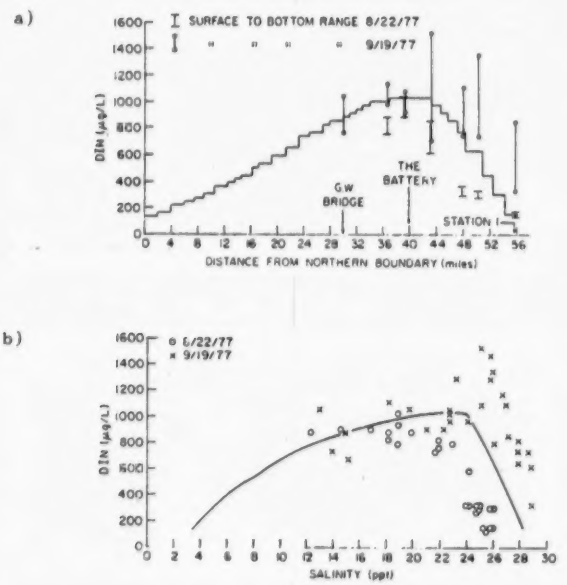

Figure AII-3. Fit of dissolved inorganic nitrogen data to a) distance from northern boundary and b) salinity, August and September 1977.

The model was solved for DIN as a conservative substance employing boundary conditions of 100 ug/l DIN. Comparisons of the model solution to the vertical range of DIN data as the sum of nitrate, nitrite and ammonia nitrogen in the Harbor (Figure AII-3a) supports the conclusion that DIN can generally be considered as conservative. The salinity-DIN relationship for the Harbor compares well with the relationship within the model for DIN loading as a conservative substance (Figure AII-3b). Toward the northern end of Manhattan approximately half of the inorganic nitrogen during the two samplings was present as nitrate. Farther south in the Harbor, ammonia is the predominant nitrogen form. Garside et al. (1976) have presented similar findings for this area during summer.

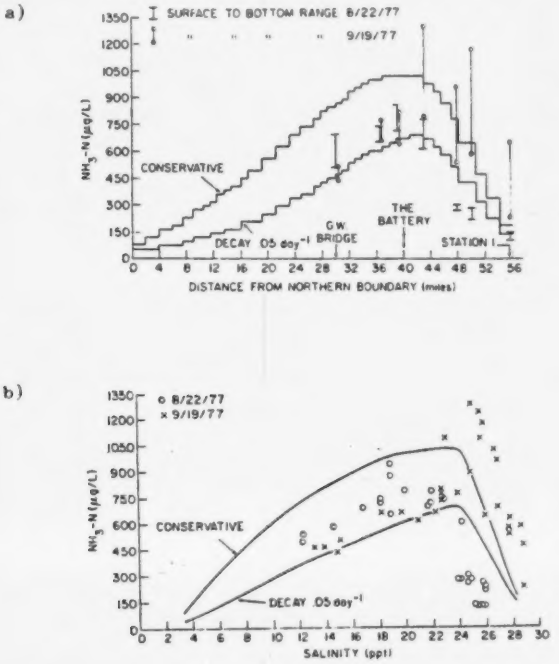

Figure AII-4. Fit of ammonia-N data to a) distance from northern boundary, and b) salinity, August and September 1977.

Model solutions for ammonia waste loadings, boundary conditions of 50 ug/l NH_3-N, with and without transformation terms, demonstrate that while DIN can generally be considered conservative, ammonia decay, due to nitrification, is apparent. The model solution that included a first order nitrification rate .06 day^{-1} in all model segments indicates this rate approximates the upper limit of nitrification for the Harbor above the Narrows. Although the Hudson River above the Battery appears to be the region where much of the nitrification is occurring (Figure AII-1), this could be an artifact of the segmentation scheme which eliminated the volume of the East River while maintaining its sewage contribution of the lower East River to the Upper Bay. Much of the nitrification probably occurs in the East River which receives

most of New York City's secondarily treated waste effluent.

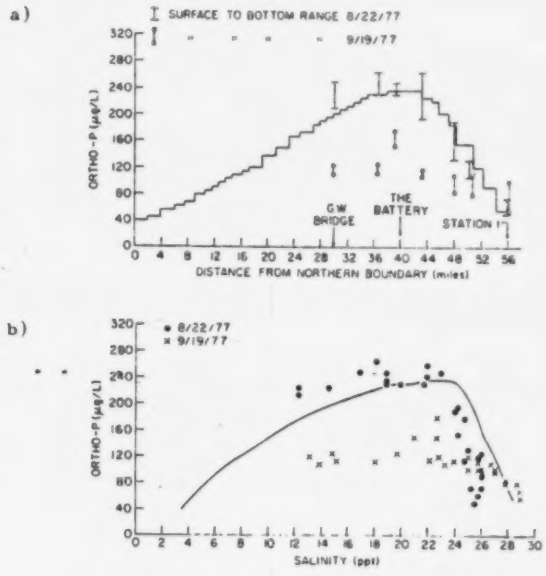

Figure AII-5. Fit of ortho-phosphate-P data to a) distance from northern boundary, and b) salinity, August and September 1977.

The high levels of suspended solids in the Hudson River north of the Battery would encourage the growth of nitrifying bacteria. Oxygen concentrations which affect the growth of nitrifying bacteria and which in turn are reduced in the nitrification process, in the main channel between the Battery and the George Washington Bridge ranged between 1.2 and 4.4 $mg \cdot l^{-1}$ on August 22, 1977 and 0.09 - 3.1 $mg \cdot l^{-1}$ on September 19, 1977. Nitrification has major implications for New York Harbor in relation to the improvement of dissolved oxygen levels that would be anticipated from further BOD removal. The response of dissolved oxygen to decreased BOD loading may be obscured by oxygen consumption in the nitrification process. The increased control of loading of substances presently inhibiting nitrifying bacteria might further stimulate nitrification. An estimate of the present upper limit of oxygen loss due to nitrification based upon a stoichiometric ratio of 4.57 grams O_2/gram NH_3-N and the model output with a nitrification rate of 0.05 d^{-1} is 1 mg l^{-1} d^{-1} dissolved oxygen.

The model was solved for soluble orthophosphate using boundary conditions of 30 ug/l and lacking a transformation term. On both sampling dates, maximum ortho-phosphate concentrations were observed in the Upper Bay. While the data for 8/11/77 conforms with the model as a conservative substance, there is an apparent departure from conservative behavior in the data for 9/19/77.

The model solution with ortho-phosphate loading, and southern boundary conditions of 30 $ug \cdot l^{-1}$ and lacking a decay term fits the data of 8/22/77 as a conservative substance (Figure 5). The data for 9/19/77 while showing maximum ortho-phosphate concentrations occurring in the same region does not fit the conservative ortho-phosphate model. The sink for the amount of ortho-phosphate not accounted for by the model is not phytoplankton since the concurrent departure in the conservative behavior of DIN that would be expected, was not observed. The concentration of suspended solids in samples taken August 22, 1977 ranged from 4.2 - 34. $ug \cdot l^{-1}$ over all stations with a mean of 24.5 1 $mg \cdot l^{-1}$. Samples collected on September 19, 1977 had a much larger concentration of suspended solids, ranging from 41.4 - 141.6 with an average of 72.7 mg/l. Total phosphorus in samples collected on both dates were comparable. Ortho-phosphate adsorption to suspended sediments appears to be the mechanism of the apparent sink in the system. Soluble ortho-phosphate is approximately 70% of the total phosphorus in municipal primary and secondary effluents (Mueller et al. 1976) and its subsequent interaction with suspended sediments in the Harbor is probably of even greater importance during high flow periods when the highest concentration of suspended sediment are found.

A large rain event that preceded the September 19 sampling probably caused the observed increase in suspended solids. Further, evidence that the steady state 5,000 cfs assumption may have been violated is found in the high concentrations of DIN and ortho-phosphate in the lower bay that are not accurately reproduced by the steady state model and may indicate the beginning of non-steady advection that resulted from the rain event.

The one-dimensional advective dispersive model provides a good framework for analysis of the data set generated here during low flow and may be the practical limit to its interpretation. The model indicates the general conservative nature of dissolved inorganic nitrogen during conditions of low suspended solids in addition to demonstrating the non-conservative nature of ammonia due presumably to nitrification processes. The model provides the quantitative link between the salinity-nutrient relationships and sewage loading (Simpson et al. 1975, 1977; Hammond 1975; Ingram 1979). In addition, the model provides support for the loading data assembled by Mueller et al. (1976).

The model supports the hypothesis that phytoplankton are of little significance to the distribution of inorganic phosphorus and nitrogen in the Harbor.

In an impact analysis of nutrient removal at New York-Metropolitan area wastewater treatment plants, the role of physical and chemical removal of dissolved phosphorus by suspended sediment in the harbor is of greater immediate importance than uptake by phytoplankton. In addition to competing for dissolved phosphorus, suspended sediment in the Harbor depresses phytoplankton growth rates by limiting light penetration to an extent that they are exceeded by flushing rates. Significantly, higher chlorophyll levels would probably result if the largely sediment-derived turbidity of the harbor was reduced. Whether the levels of suspended sediment in the Harbor could be reduced by the most massive nonpoint source control expenditures is doubtful.

If classified by transparency or nutrient concentrations, the Harbor would be accurately described as hypertrophic. However, implicit to trophic classification by transparency and nutrient concentrations is that light extinction is caused primarily by photosynthesis organisms, the biomass of which is relatively predictable based upon nutrient concentrations. Unlike systems such as the Potomac Estuary and other areas of the Chesapeake Bay system where sewage derived nutrients result in massive algal blooms in the immediate receiving waters (Thomann et al. 1974; Salas and Thomann 1978; Seliger and Loftus 1974), our work and the work of Garside et al. (1975) demonstrates that only a small percentage of the nutrients loaded by wastewater to the Harbor are utilized within its boundaries. The much larger portion of soluble nitrogen and phosphorus is delivered to the large and hydraulically active area of the New York Bight Apex where these nutrients are dispersed and rapidly assimilated by phytoplankton (Malone 1975). Even in the Apex, phytoplankton blooms are not chronic water quality problems.

In relation to the goals of the Clean Water Act for swimmable and fishable waters, nutrient removal from wastewater sources into New York Harbor should only be considered in relation to measures taken to reduce the suspended sediment concentrations in the Harbor. While turbidity and to a certain extent excessive algal biomass are generally aesthetic impediments to fishable and swimmable waters, the human health aspects would appear to be the priority targets of remedial expenditures.

Bacterial and viral contamination of contiguous beaches and shell fisheries due to combined sewer overflows, the closing of fin fisheries due to toxic substances is the major but not only culprit, and the high potential for oil spills in the Harbor appear to be such priority impediments to the goals of the Clean Water Act that will require massive expenditures of water pollution abatement resources for their remedy.

APPENDIX II

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